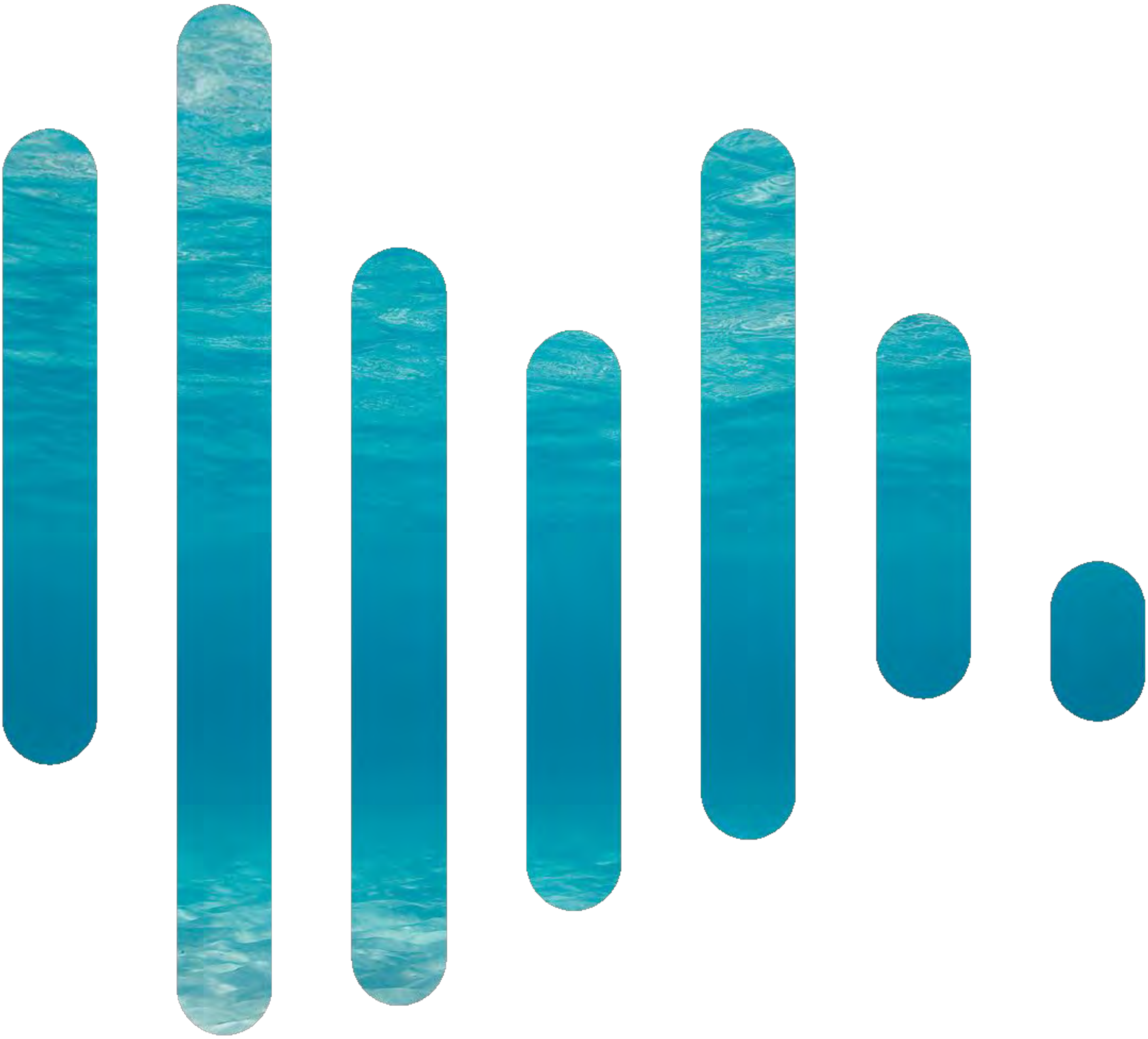
TECHNICAL APPENDIX 5.6

IRWIN CARR
CONSULTING



Hatston Pier, UW Noise Modelling

Kirkwall, Orkney

RP001 2022248 (Hatston Pier, UW Modelling)

19 January 2023

PROJECT: HATSTON PIER, UW NOISE MODELLING

PREPARED FOR: ENVIROCENTRE

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EXECUTIVE SUMMARY

BRIEF DESCRIPTION OF WORK

In relation to the expansion of the pier at Hatston, both dredging, piling and blasting will be carried out. The noise from these activities can adversely affect local fauna either through direct injury of sensory systems or indirect harm from noise pollution drowning out communication and foraging sounds. We here model the noise emission from the various noise sources to estimate impact from noise and what mitigation can/needs to be employed to keep impacts below levels of significant harm to the local wildlife.

Source sources (dredging, piling and blasting) are modelled from a combination of empirical models (based on recorded data) and numerical models (calculated source levels from inputs).

CONCLUSION & RESULTS SUMMARY

Blasting

Blasting has the largest risk ranges, with two groups exceeding a 500 m range (baleen whales and porpoises) for hearing injury (PTS). Also, the risk range for PTS for peak pressure is 100-375 m for multiple animal groups. As the blasting has no slow build-up of noise or soft-start and leaves no time for the animals to vacate the area, it is important that mitigation be put in place to facilitate the clearing of marine mammals in the area prior to blasting. Having a qualified Marine Mammal Observer (MMO) observe the area for a 30-minute duration prior to commencing blasting is a common procedure. Given the sheltered condition of the bay, extending the monitoring range to 725 m should be possible.

We note that this assessment has used the upper bound of both amount of explosive used, number of blasts and energy transfer to the water, so it is very unlikely that the real risks are as high as presented here.

Dredging

The noise from dredging, while presenting a significant hearing injury (PTS) risk to ranges >100 m for baleen whales and porpoises, this is only for animals staying close to the activity for extended periods. There is no acute risk of noise related injury related to the dredging, and animals have time to swim away.

Vibro piling

Even prolonged exposure to vibro piling at close range (<100 m) carries little to no auditory risk for the animals assessed.

Table of Contents

Abbreviations and Definitions:

SSP	Sound Speed Profile
Hearing group	Refers to the Southall 2019 hearing groups (Southall, et al., 2019).
“,” and “.”	Comma “,” is used as thousands separator, while dot “.” Is used as decimal separator.
TL, PL	Transmission Loss, Propagation Loss. Used interchangeably in this document.
Psu	Practical salinity unit, equivalent to parts per thousand as g/kg, mass of salts per mass of water.
Noise	Sound that causes, or is assumed to cause, annoyance or disadvantage. No automatic significance of impact is associated with this term.
Solver	Mathematical algorithm for calculating sound transmission losses in water.
[]	Square brackets are used throughout to denote units, e.g.: “Pressure [Pa]” means pressure in Pascals.
Degrees	Either angular degrees (0-360) or degrees Celsius
3rd octave, decidecade	Refers to the subdivision of octaves (doublings of frequency) and decades (10x frequency). Using the appropriate base frequency, the two are identical for practical purposes.
Worst case	Used as “reasonable worst case”. E.g. use of MHWS instead of historical maximum for max water level. Or 90th percentile as representative of worst-case.
Mean case	The expected case, both median and mean values will inform this.
Signature, Impulse	When in relation to a sound, this refers to the time-pressure signal associated with that sound, normally as a time-series of pressures relative to ambient pressure, in pascals.
Vibro	Vibration pile driving
MSL	Mean Sea Level
β, Log multiplier	Symbol used to denote the factor multiplied by the base ten Log in equations like: “$TL = \beta \times \text{Log}_{10}(\text{range})$”
SL, Source level	Apparent monopoint source level as viewed from the acoustic far field

1 INTRODUCTION

In relation to the expansion of the pier at Hatston, both dredging, piling and blasting will be carried out. The noise from these activities can adversely affect local fauna either through direct injury of sensory systems or indirect harm from noise pollution drowning out communication and foraging sounds. We here model the noise emission from the various noise sources to estimate impact from noise and what mitigation can/needs to be employed to keep impacts below levels of significant harm to the local wildlife.

Source sources (dredging, piling and blasting) are modelled from a combination of empirical models (based on recorded data) and numerical models (calculated source levels from inputs).

1.1 Underwater Acoustics Basics

Underwater acoustics modelling is the application of physical models to characterise the behaviour of sound in environments under the surface of the sea and in the top layers of the seabed. As some familiarity with in-air acoustics is assumed the focus here is on key differences between in-air acoustics and underwater acoustics, making waterborne propagation more efficient than airborne propagation.

This chapter only gives reader a quick overview, please see APPENDIX B – Underwater Acoustics Basics APPENDIX *for more detail.*

1.1.1 SOUND SPEED

Water is much harder to compress than air, and a soundspeed of 1500 m/s is often used as a standard soundspeed in water[1] much as 340 m/s is in air.

The soundspeed changes with depth, “sound speed profile”, this is quite important in sound propagation, as refraction (changes in propagation angle) will occur when sound moves between layers of water with varying sound speed. These effects can lead to profoundly inhomogeneous sound fields and SOFAR channels.

The same relationships are valid in the sediment, though sediments commonly have soundspeeds higher than water. Soundspeeds from 1700 m/s (fine sand/silt) to 2500 m/s (gravel) are common for non-solid sediments, with solid sediments (rocks) having much higher soundspeeds 2800 m/s (Calcarenite) to 6000 m/s (some granite).

1.1.2 SPREADING LOSS

Most of the propagation loss (loss in dB from source to receiver, “PL”) that occurs initially is governed by “spreading loss”. It is the simple “thinning out” of acoustic energy as it spreads away from the source, usually in all directions – spherically. This means a reduction in received level of 6 dB per doubling of distance

At longer ranges the medium is no longer unbounded. We reach ranges where the sound has interacted with the surface (near perfect acoustic reflector) or the seabed (lossy acoustic reflector). Here we expect spreading loss to be ~3 dB per doubling of distance.

1.1.3 ABSORPTION

Besides the “thinning out” of the sound energy as described above, the sound is also dissipated into heat by the way the pressure changes interact with water, molecules and particles in its path. This absorption is salinity dependant. Frequencies under 1 kHz experiences almost no absorption, while high frequencies, over 10 kHz, can be attenuated by over 10 dB / km.

Small bubbles, wind or wave induced, will further attenuate especially the high frequencies.

1.1.4 SEDIMENT

Depending on the incident angle of the sound, the frequency and the acoustic properties of the sediment, sound can either mostly penetrate the sediment or mostly be reflected by it.

In shallow areas with soft sediment (acoustically similar to water), it is typical to find that close to the source, at high incidence angles and at low frequencies (<250 Hz) the sound will penetrate into the sediment and dissipate there, leading to very high transmission losses for these frequencies.

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[1] Varies from 1450 m/s at 0° to 1550 m/s at 30° at salinity of 35 psu.

1.1.5 SOUND LEVEL UNITS

All references to sound pressure levels, peak pressure levels and sound exposure levels refer to a logarithmic ratio between a reported/measured pressure or exposure and a reference pressure or exposure. As an example, a level of 220 L_p (decibel zero-to-peak) is equal to a peak pressure of 100000 Pascals (Pa) over ambient pressure, while 120 L_p is equal to 1 Pa over ambient pressure.

To avoid dealing with these large numbers as pascals (as a linear scale), they are converted to a decibel ratio (Table 1 for definitions). Besides compressing large numbers to a smaller scale this also corresponds better to how animals are thought to perceive sound, namely as relative steps. This means that an increase from 1 to 2 Pa *sounds like* the same increase as from 100 to 200 Pa, even though the first step was only 1 Pa, while the second was 100 Pa. This is better reflected in a logarithmic scale based on ratios, where both steps are equal, here 3 dB.

However, while dBs are practical, they can be hard to compare between studies, due to vague definitions, and so we have adopted the standards set by ISO 18405-2017 (Table 1 below).

For ease of reference please see following overview for unit definition.

Table 1: Definitions.

Unit	Definition	Comments
SPL (dB_{RMS}) ISO 18405- 2017: 3.2.1.1	$SPL = 10 \cdot Log_{10}\left(\frac{\frac{1}{t_2 - t_1} \cdot \int_{t_1}^{t_2} p(t)^2 dt}{1 \cdot 10^{-12} Pa}\right)$	Functionally equivalent to deprecated $20 \cdot Log_{10}\left(\frac{RMS}{1 \cdot 10^{-6} Pa}\right)$
L_p ($dB_{z\text{-}p}$) ISO 18405- 2017: 3.2.2.1	$L_p = 20 \cdot Log_{10}\left(\frac{Pa_{max}}{1 \cdot 10^{-6} Pa}\right)$	This assumes that Pa_{max} is equal or greater than $\sqrt{{Pa_{min}}^2}$
$L_{p\text{-}p}$ ($dB_{p\text{-}p}$)	$L_{p-p} = 20 \cdot Log_{10}\left(\frac{Pa_{max} - Pa_{min}}{1 \cdot 10^{-6} Pa}\right)$	Often[2] equivalent to $L_P + 6.02\ dB$
L_E (dB_{SEL}) ISO 18405- 2017: 3.2.1.5	$L_E = 10 \cdot Log_{10}\left(\frac{\int_{t_1}^{t_2} p(t)^2 dt}{1 \cdot 10^{-12} Pa}\right)$	For continuous sound this is equivalent to $SPL + 10 \cdot Log_{10}(t_2 - t_1)$ “t” is seconds

Unless otherwise stated SPL has an averaging period of 1 second, and L_E for the duration of the specified event, sometimes indicated as $L_{E\text{-“time”}}$ or $L_{E\text{-single blow}}$.

If the averaging period for SPL is equal to the total even duration then SPL is equal to “Leq” the “equivalent constant level”.

When source levels are presented, the same units are used, and it is implicit that all source levels are given as if recorded 1 m from an omnidirectional mono-point source, unless otherwise specified.

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[2] If maximum pulse rarefaction is below ambient pressure and compression and rarefaction phases are of equal size.

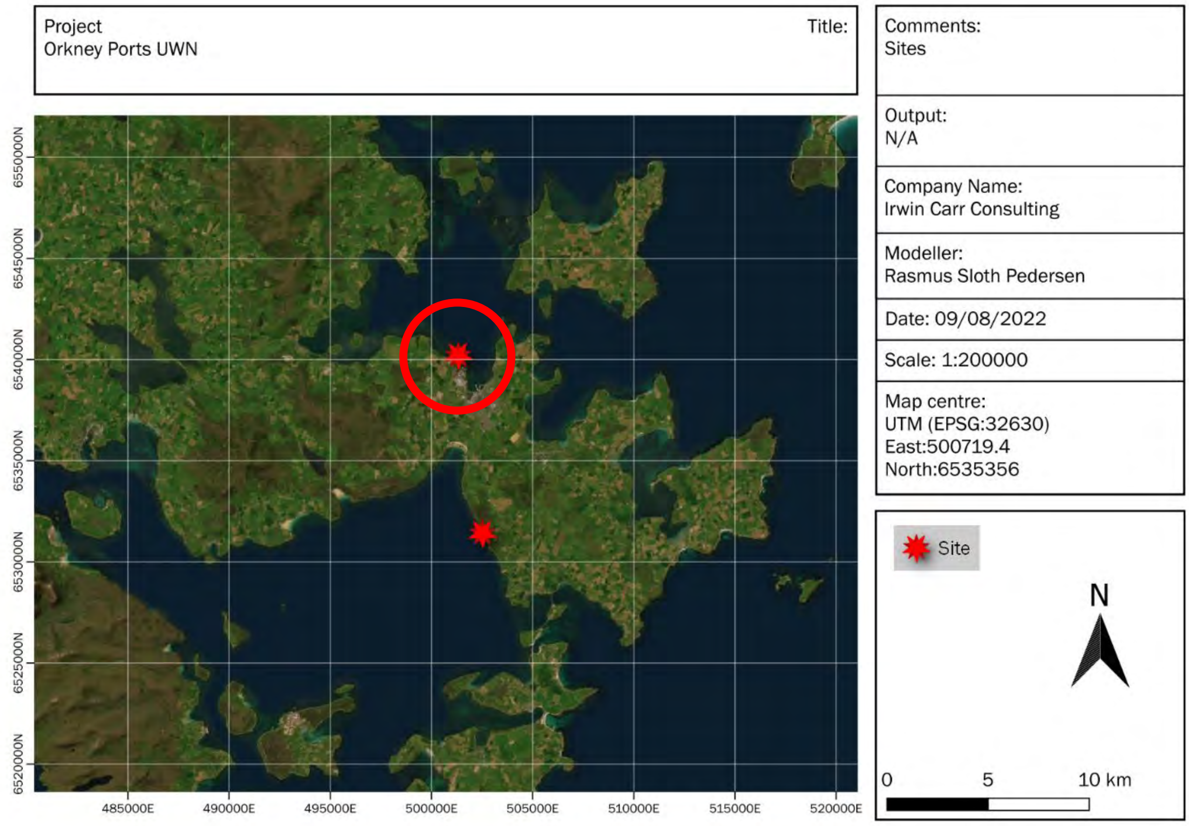
2 SITE AND LOCAL ENVIRONMENT

The site is located in Orkney, Scotland:

- Hatston Pier at Lat: 59.002115, Lon: -2.970403, Mean water depths 5-15 m.

The site is sheltered from oceanic swell, with little current and with no major outflows from rivers, meaning that the conditions important for sound propagation are quite stable. The sediment is generally a soft upper layer of mud/silt and gravel overlaid a layer of weathered sedimentary rock, before a stronger layer of sedimentary rock (silt-/mud-/sand-/lime-stone).

Figure 1. General location of the Hatston pier (in red circle) on Main Island of the Orkney Islands. Scapa site (in Scapa flow, south of Kirkwall shown for completeness).



Project
Orkney Ports UWN

Title:

Comments:
Sites

Output:
N/A

Company Name:
Irwin Carr Consulting

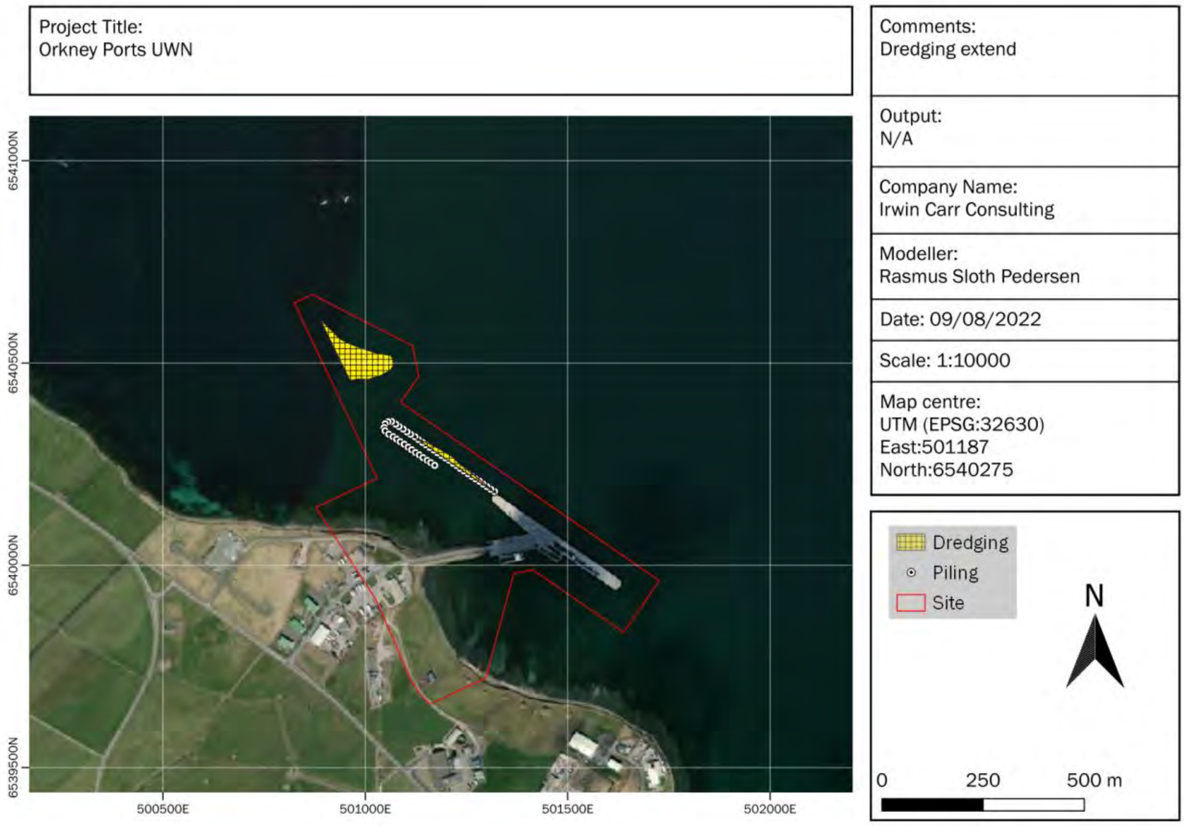
Modeller:
Rasmus Sloth Pedersen

Date: 09/08/2022

Scale: 1:200000

Map centre:
UTM (EPSG:32630)
East:500719.4
North:6535356

Figure 2. Overview of assumed piling/blasting locations and approximate areas to be dredged (small area next to piling hard to see at this scale).



2.1 Depth, Bathymetry

Depth data for the sites were collected from 3 sources:

- The proponent, detailed data near the sites, 4 m resolution.
- EMODNet (European Marine Observation and Data Network, 2019), long range data, ~90 m resolution.
- Nautical charts such as http://fishing-app.gpsnauticalcharts.com, medium range data, variable resolution.

These were corrected to MSL and combined (using a mosaic method) to give the best possible total cover of the area.

The MHWS (Mean High Water Spring) level is used (deeper water decreases sound transmission loss).

2.2 Water properties

The water properties are important for the sound propagation. Generally the two sites have no major outflows of fresh water so salinity is expected to be near 35 psu (confirmed by (Marine Scotland, 2022)).

2.2.1 TEMPERATURE

The temperature was measured for with the inbuilt thermometer of the Soundtrap hydrophone (used for on-site measurements).

Water temperature at Hatston site: 9.1 °C

The water columns are assumed to be well-mixed, given lack of nearby freshwater outflows, windy location, evaporation and generally shallow depths (<30 m).

2.2.2 SOUNDSPEED PROFILE

Given the water properties given above we assume the water soundspeed to be constant at all depths, with no significant deviations from the expected values.

The sound speed calculation is based on a widely used model for sound speed in water (Leroy, Robinson, & Goldsmith, 2008), with input of temperature, depth and salinity.

Sound speed in water is calculated as 1486 m/s

2.3 Sediment properties

Given the project is a construction project there is ample sediment cores available for sediment characterisation provided by “Causeway Geotech”. These give good coverage in the areas close to the Hatston Pier/Scapa DWP. For general sediment types further away, we have used data from British geological survey (British Geological Survey, 2022).

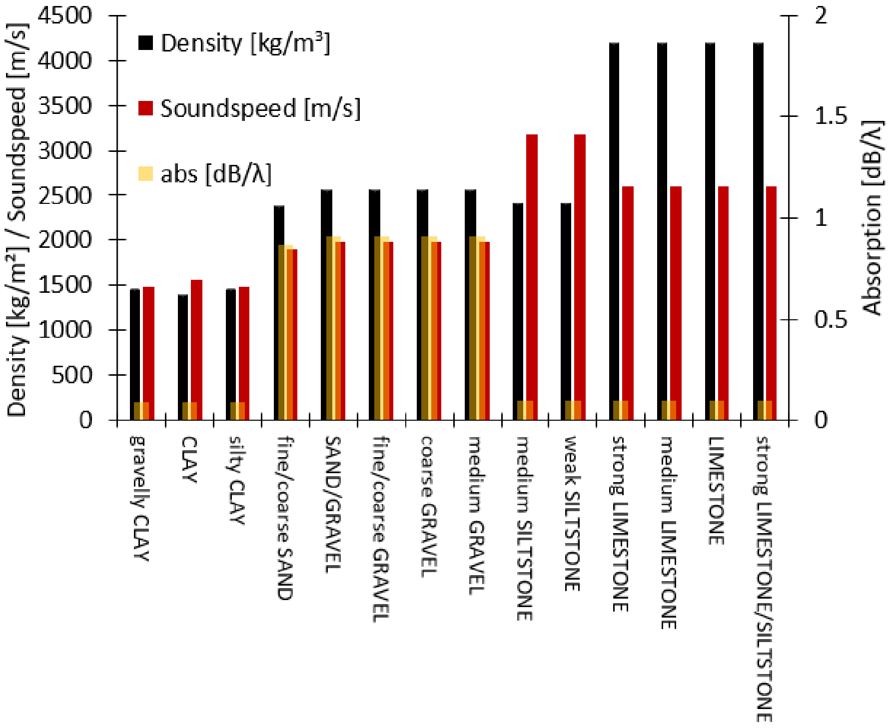
For the boreholes we mapped the descriptions in the sediment core reports in relation to their Udden-Wentworth or Folk sediment description where these matched the nomenclature well. For other sediment types, e.g. sandstone/mudstone/limestone we have used given values for nominal “sandstone” (Jensen, Kuperman, Porter, & Schmidt, 2011; Boyce, 1981). The cores also contain classifications such as “weak sandstone” this was interpreted as loose, sandy sandstone, and we characterised this with density and soundspeed between that of sandstone and sand. This interpolation was based on an assumption that the scale “very weak-, weak-, medium weak-, sandstone” corresponds to linear interpolation between sand and sandstone (see Table 2 below). We have not changed the properties for categories indicating harder than usual sediments, such as “medium strong”, “very strong“.

Table 2. Example of interpolation scheme for Sand-sandstone.

Material	Interpolation value	Density [kg/m^3]
Sand	0	1931
Very weak sandstone	0.25	2111
Weak sandstone	0.5	2291
Medium weak sandstone	0.75	2470
Sandstone	1	2650

Where we had no direct properties (density, sound speed, absorption) for the sediment we have used a modelling approach to estimate them, following (Ainslie, 2010).

Figure 3. Sediment types. Note that absorption is read on the right vertical axis.



2.4 Background/Ambient Noise

On both days/sites (Visit at Scapa site in connection with this report) the weather was very calm (< sea state 1) with no detectable current. The Scapa site was unexpectedly noisy with ~130 dB SPL for all measurements (unaffected by range to our vessel). There were multiple other vessels in the bay, but all far away (> 1km). The most likely source was the small oil platform stationed a few km to the south. This could have some active machinery causing the noise, indicated by the tonal components (seen as horizontal bands in spectrogram in Figure 4, p. 12).

Ambient noise at Hatston was in the expected range for inshore waters.

Note that ambient noise here excludes noise from nearby vessel passes, it is meant as the ambient noise with no identifiable noise sources.

Table 3. Typical background noise levels at the two sites.

Site	SPL [dB]
Scapa	129.9
Hatston	107.2

Figure 4. Spectrogram of ambient noise at Scapa.

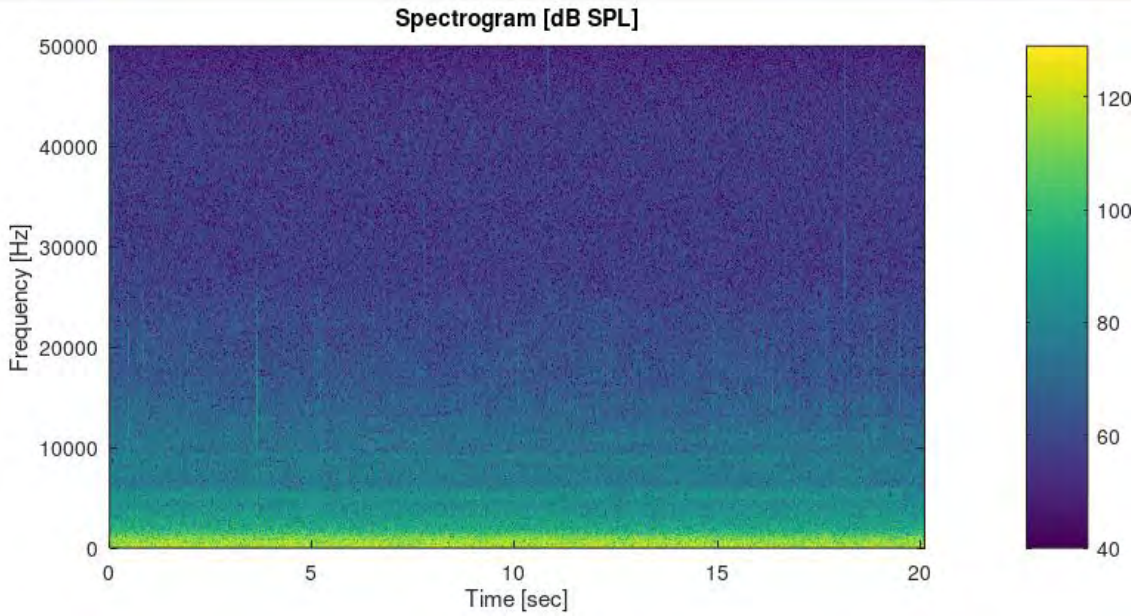


Figure 5. Spectrogram of ambient noise at Hatston.

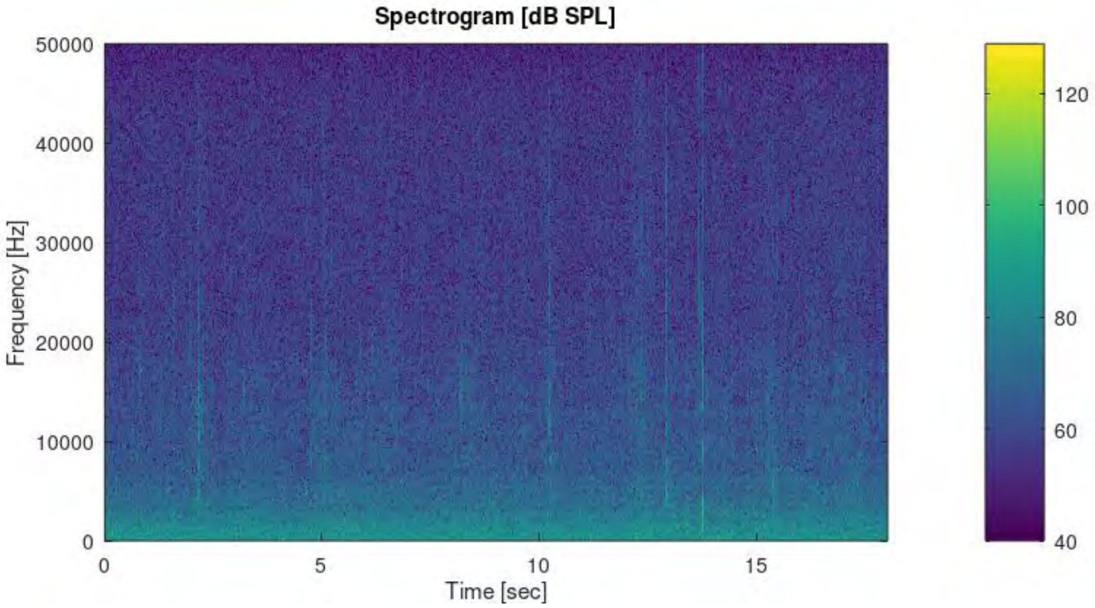
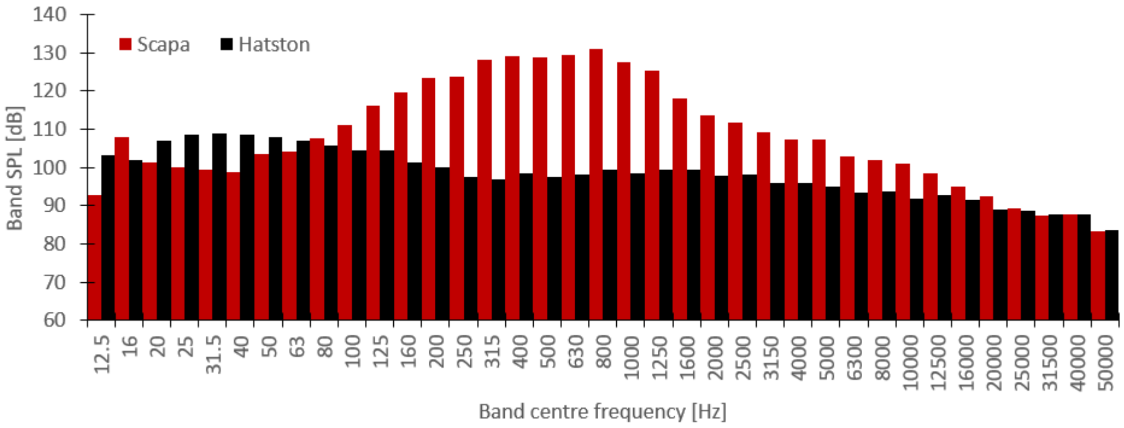


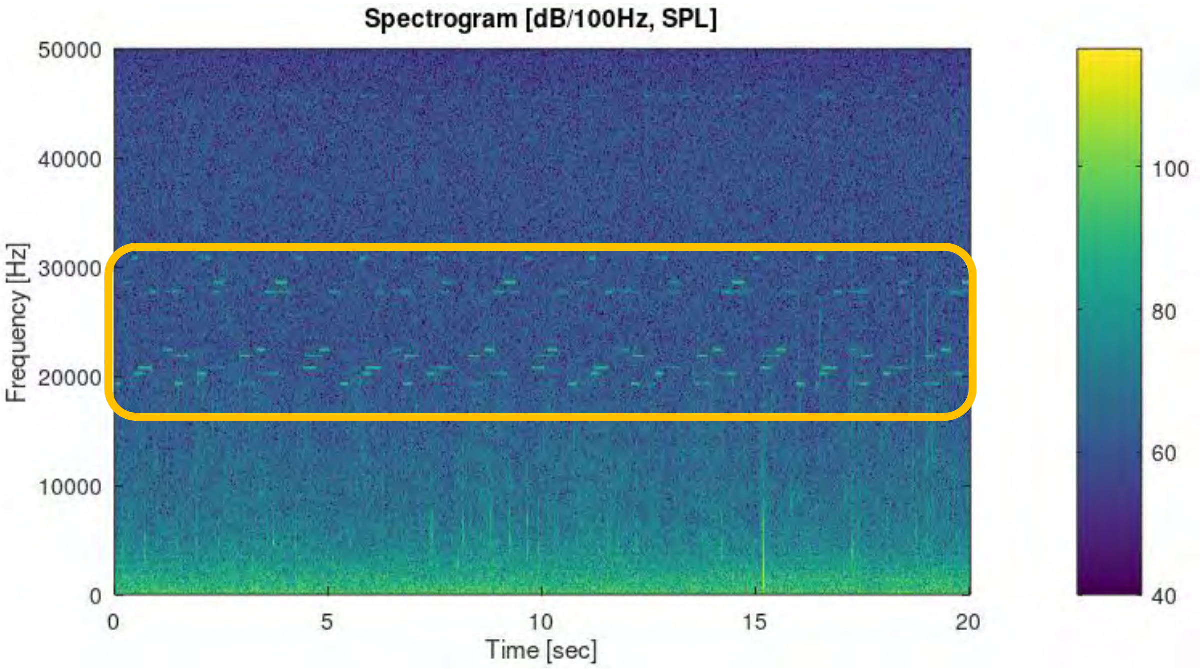
Figure 6. Typical band levels of ambient noise at Scapa (129.9 dB SPL) and Hatston (107.2 dB SPL).



2.4.1 NEARBY FISH FARM

We note that a nearby fish farm (~500 m NW of the Hatston transects) uses what is presumably ADDs (Acoustic Deterrent Devices / Seal scarers). We present these here to keep in mind as part of the soundscape for a later acoustic impact assessment. A rough estimate for the source level for the ADDs is 100-120 dB SPL per Hz at 20-22 kHz and 28-30 kHz.

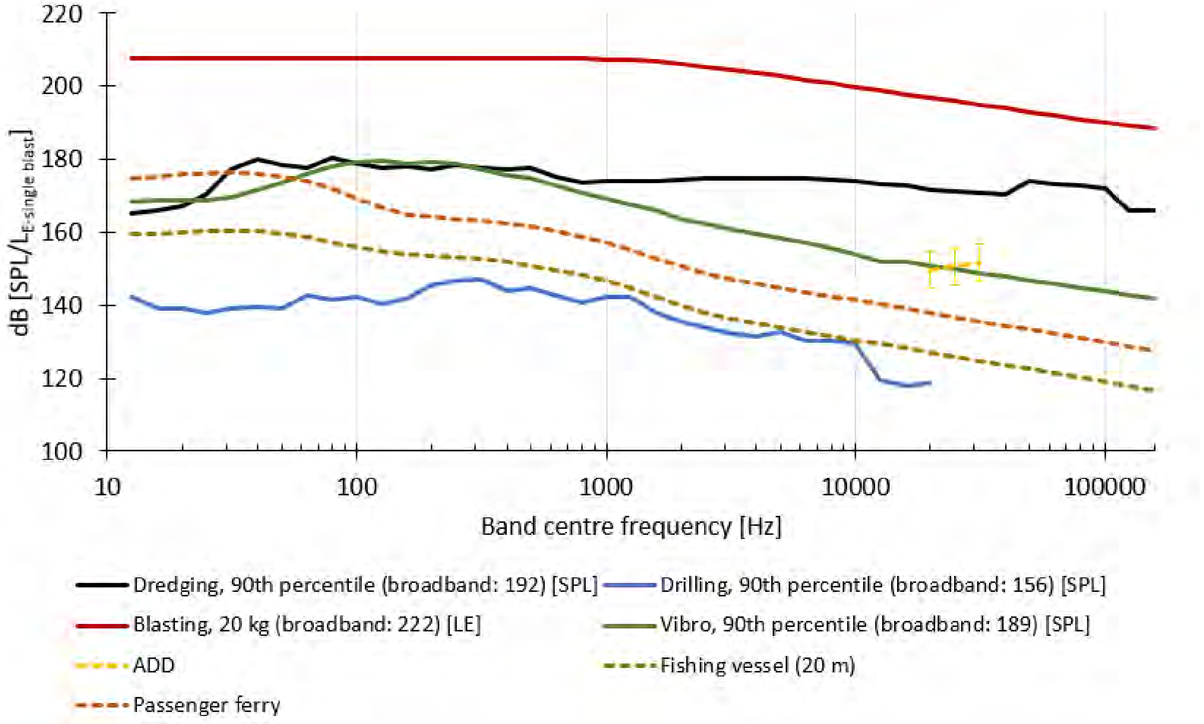
Figure 7. Spectrogram showing what is presumably one or more ADDs (Acoustic Deterrent Devices / Seal scarers) at the fish farm northwest of Hatston in Figure 2, p. 10. ADD pulsed are ~66-70 dB SPL/Hz, which at 500 m range might mean 100-120 dB/Hz at the source.



3 SOUND SOURCE MODELLING

We have considered four noise sources for this assessment, but have screened out the drilling as it not loud enough to meaningfully assess in an environment with many vessels and general human activity (compare with vessel noise in Figure 8, below).

Figure 8. The four sound sources considered in this report. The ADD from the fish farm (yellow), a fishing boat and a small ferry has been added for context.



3.1 Blasting

Due to the hard sediment underlying the sediment at Hatston blasting is planned prior to pile installation.

It’s estimated that blasting will be necessary at 1 m intervals along the line of pile installation at the new section of the pier (Figure 2, p. 10, same as markers names “Piling Hatston”). This segment is 500 m long, meaning an expected 500 boreholes for blasting. Charges for each hole is estimated by the contractor at 15-20 kg TNT equivalent with 4-6 holes per day. Blast will be staggered in time to avoid simultaneous blast waves, but are assumed to be close in time with all blasts detonated within 1 minute. This results in a range of 60-120 kg TNT equivalent detonated daily.

From previous experience about 5-10% of the acoustic energy from the blast makes it into the water column. We have assumed 10% here as a conservative measure.

We have used the models from (Soloway & Dahl, 2014) to generate an idealised impulse for the blasting. These impulses will not match recordings, but the intention is to match the true peak pressure level (L_P) and the true impulse energy (as L_E).

Figure 9. Assumed timeseries for 15 kg TNT equivalent detonation at 1 meter. This is an idealised impulse and will not correspond directly to a measured impulse.

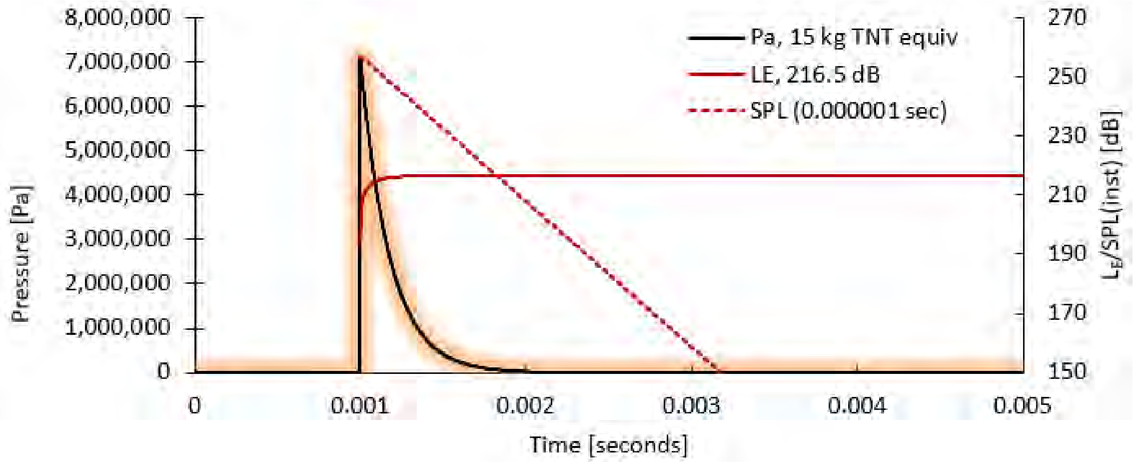


Figure 10. Assumed timeseries for 20 kg TNT equivalent detonation at 1 meter. This is an idealised impulse and will not correspond directly to a measured impulse.

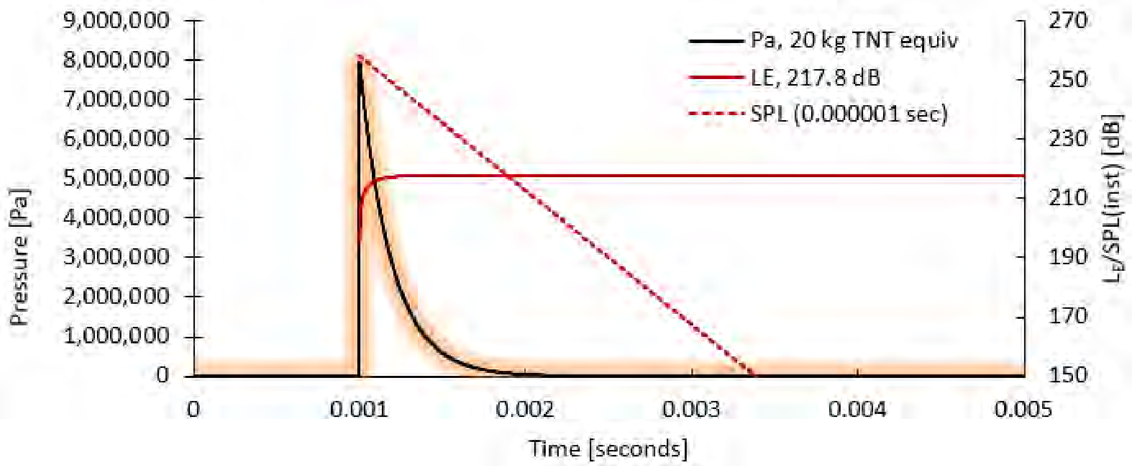


Table 4. Assumed in-water equivalent source levels for blasting

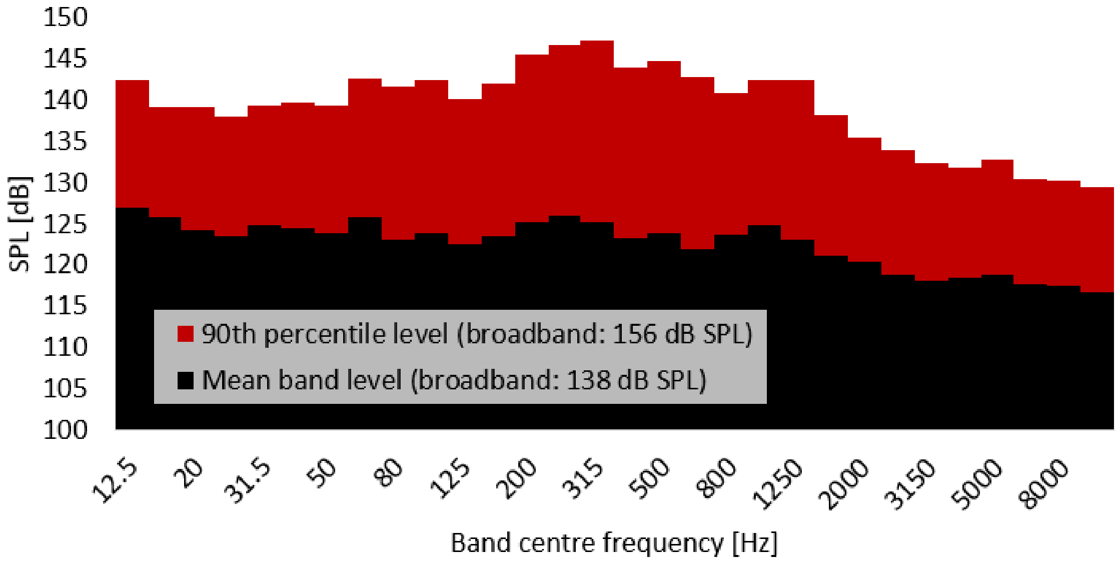
	Source level [dB]
L_P	258
$L_{E\text{-single blast}}$	218

3.1.1 DRILLLING

As all explosives will be placed in holed prior to detonation, drilling will take place for each blast. While drilling through hard sediment can be significantly noisy, given that the drilling is to occur in a similar time period to the blasting the noise from drilling will be dominated by the acoustic impact of the blasting.

A summary of 13 different recorded drilling episodes shows noise levels to vary considerably between sites and equipment, and there is no clear connection between drill size, power or sediment type to the emitted noise level. However, given the modest broadband level of even the 90th percentile level (156 dB SPL) this noise source can be ignored.

Figure 11. Example of drilling noise band levels. Data from various drills, diameter 0.1-1.2 m and various rock types.

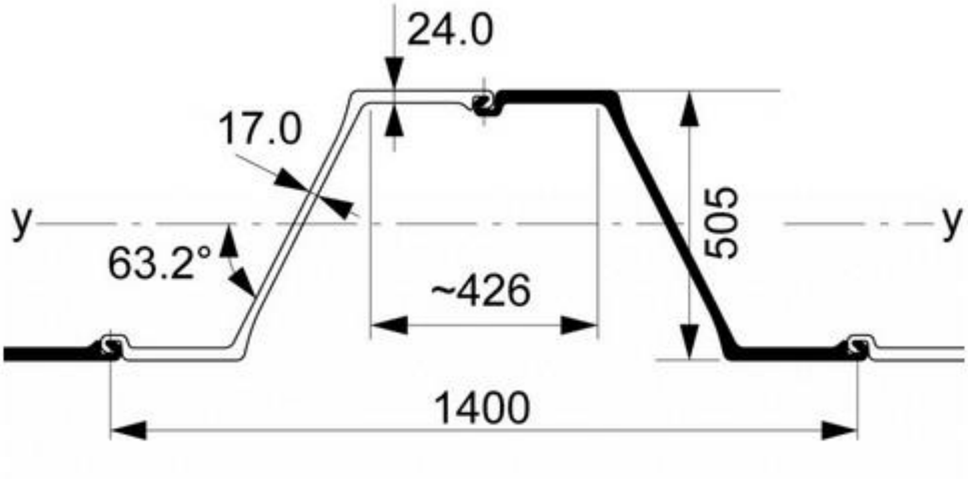


3.2 Vibration Piling Model

Details in APPENDIX C – Source Models

The piles used for the pier extension are sheet piles (Arcelor Mittal AZ52-700[3]). These will be vibrated into the trench created by the blasting operation.

Figure 12. Schematic of the sheet piles profile.



The diagonal of a single sheet (86 cm) is used a basis for an empirical model based on 50 recorded levels as from CalTrans (CalTrans, 2015).

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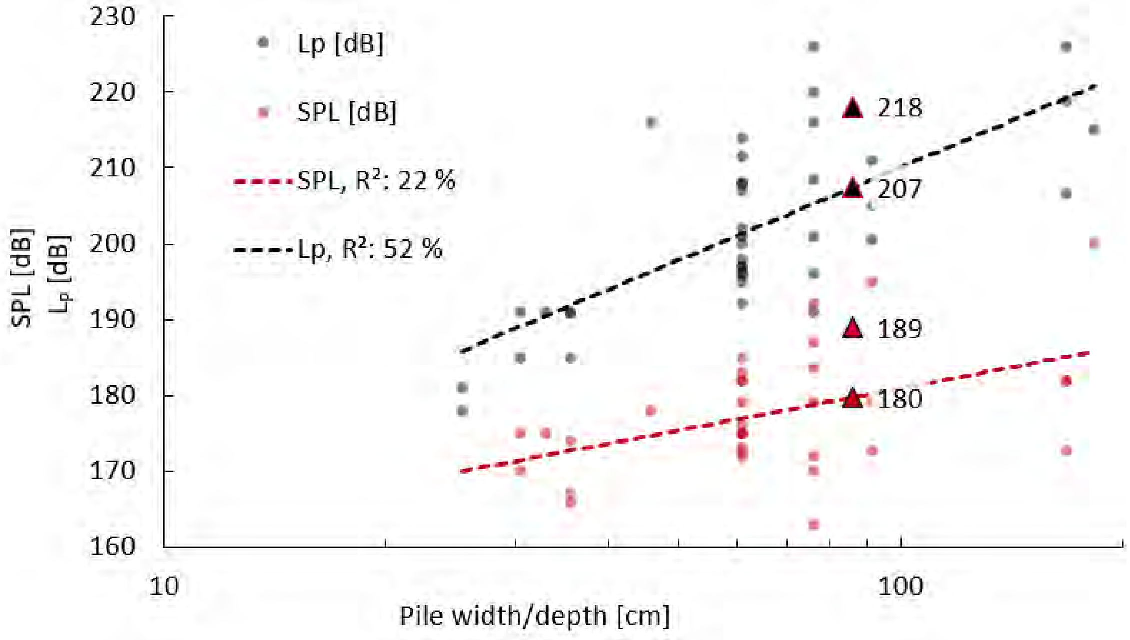
[3] https://sheetpiling.arcelormittal.com/products/az-52-700/

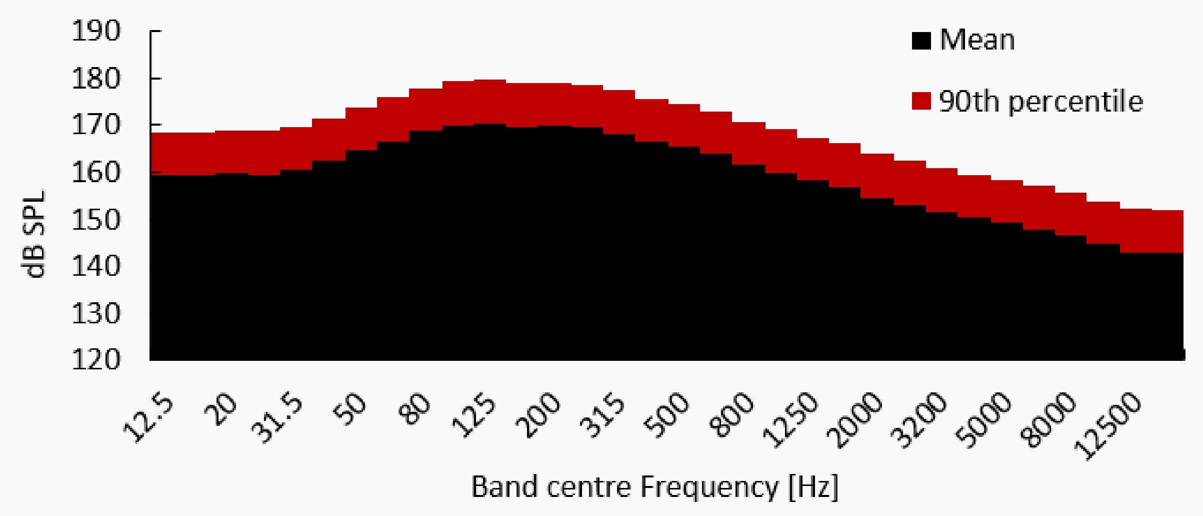
Figure 13. Basis of vibro piling broad band source level as a function of pile size (86 cm diagonal).



Given the low confidence we have in this approach (low R^2 values) we use the 90th percentile level as the broadband source level. L_P is estimated to be 218 dB and SPL 189 dB. The frequency content is assumed to be identical to that of the impact piling.

It is assumed that there will be active piling maximally 8 hrs of every 24 hrs.

Figure 14. Band levels for vibro-piling.



3.3 Dredging

Dredging is done to chard Datum -10 meters, meaning this will likely be done with a cutter suction dredger (Max reach 15 m). A cutter power of 540 kW is assumed, equivalent to the Boskalis “Seine”[4] cutter suction dredger. For cumulative modelling it’s assumed that the dredging is active for 8 hrs every 24 hours.

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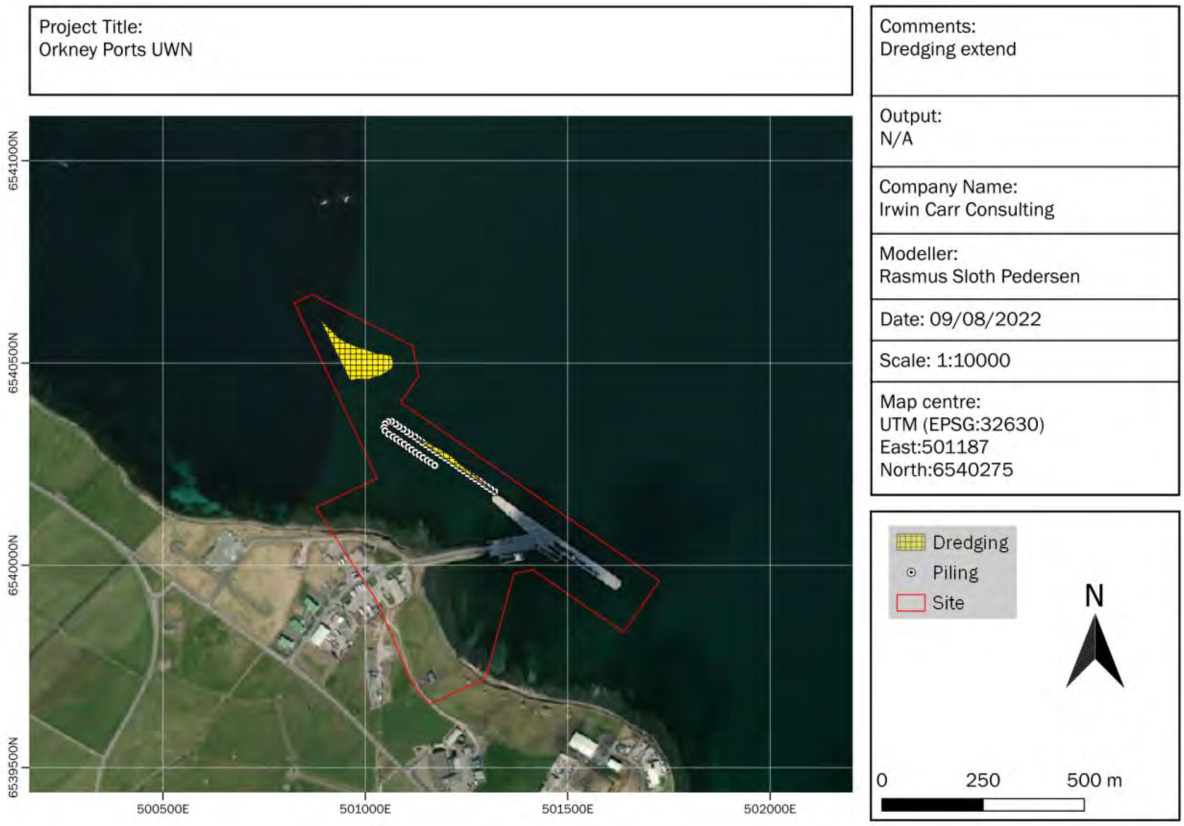
[4] https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwibnqWF-sH8AhUQg1wKHfYmBVoQFnoECB8QAQ&url=https%3A%2F%2Fboskalis.com%2Fmedia%2Fqbjnfdlv%2Fseine_cutter_suction_dredger.pdf&usg=AOvVaw1bBD75xRPcFc3H0TUXTFkD

Figure 15. Approximate extend of dredging campaign (yellow hatched area).



Project Title:
Orkney Ports UWN

Comments:
Dredging extend

Output:
N/A

Company Name:
Irwin Carr Consulting

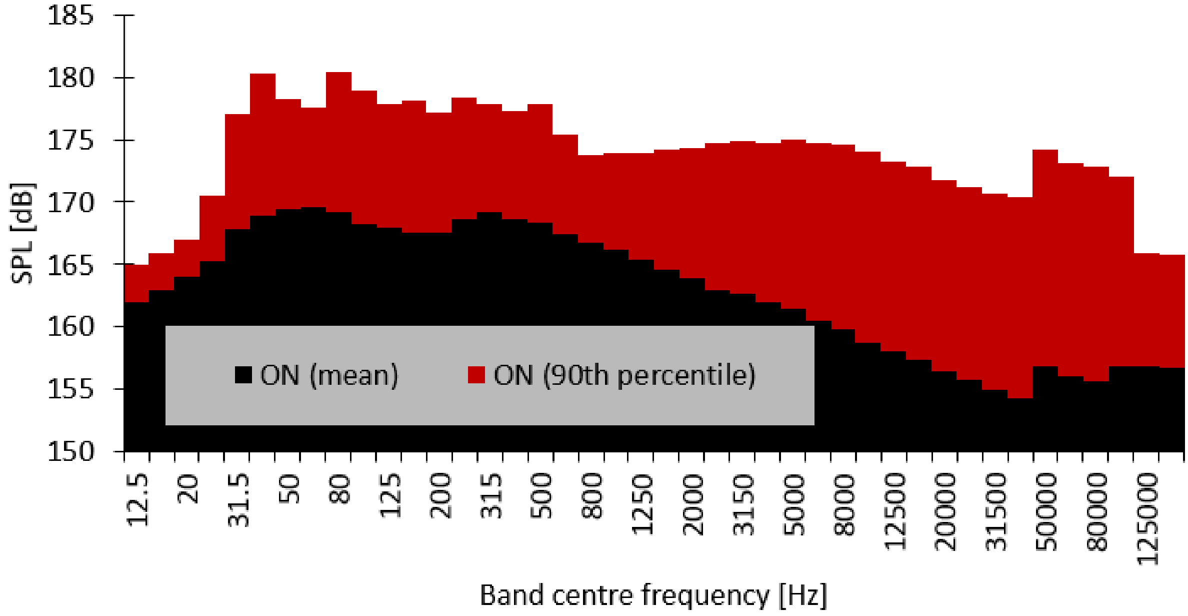
Modeller:
Rasmus Sloth Pedersen

Date: 09/08/2022

Scale: 1:10000

Map centre:
UTM (EPSG:32630)
East:501187
North:6540275

Figure 16. Band levels as modelled for a 540 kW cutter suction dredger with coarse sediment. "ON" refers to active dredging.



4 TRANSMISSION LOSS MODELLING

Transmission loss modelling is done using dBSea underwater noise modelling software.

This software is partially developed by us and can model frequencies from 10 Hz to 168 kHz, normally as 3rd octave bands, but any logarithmic band-spacing can be used. All solvers are range dependent (meaning all conditions can change with range not just depth).

Further details of this modelling software package can be found in APPENDIX A - dBSea.

The sound sources from section 3, Sound Source Modelling, p. 15, was used sources for the model, both as band levels when modelling energy transmission losses (L_E, SPL) and as timeseries/impulse for modelling peak pressure (L_P).

Previous to this assessment measurements of the actual transmission loss for the two sites were measured along two transects for each site. The modelling has been calibrated to match the measurements of these recordings (details in APPENDIX D –).

The measurements show a broadband transmission loss consistent with ~12 × Log_{10}(range) at Scapa and ~22 × Log_{10}(range) at Hatston. However, these are frequency specific, and these losses are not consistent across all frequencies. We have matched the frequency-wise transmission losses to the extend that they are less than 20 × Log_{10}(range) as we find it unlikely that a transmission loss, even for higher frequencies, of > 20 × Log_{10}(range) is sufficiently representative for the site as a whole.

5 ASSESSMENT CRITERIA

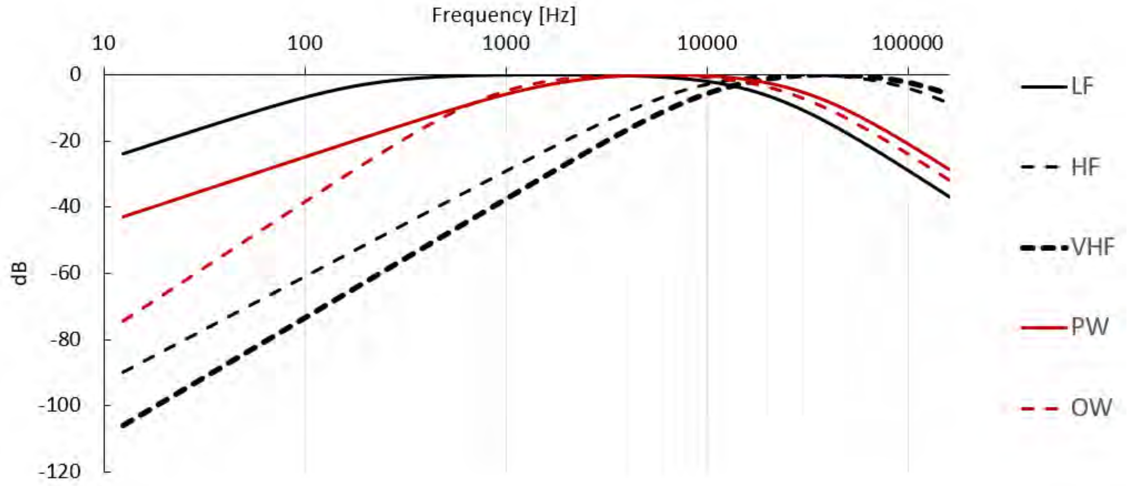
5.1 Reporting units

See 1.1.5, p. 8 for definitions.

5.2 Weighting of Noise Levels

When not reporting L_p or $L_{p\text{-}p}$ levels, the noise levels are often weighted according to a generalised hearing sensitivity profile for up to ten different hearing groups. This is done to better reflect the actual impact on the species in question, much like dB(C) level unit for humans.

Figure 17. Weightings for various hearing groups. For L_E levels, the weightings are applied to the noise level to give the weighted noise level (similar to dB(A) or dB(C)-weighted noise for humans).
See Table 5, p.21 for full group names and limits.



5.2.1 MARINE MAMMAL WEIGHTINGS

For the marine/aquatic mammals present we will adhere to the thresholds described in "Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing" (National Marine Fisheries Service, 2018), which determines impact from an assessment of area wherein the noise will induce either "Temporary Threshold Shift" (TTS) or "Permanent Threshold Shift" (PTS)[5] as judged by the weighted SEL level ($L_{E\text{-}24}$) over a typical 24-hour period or by L_P levels, for the different hearing groups.

Please note that the Southall 2019 thresholds and weightings are identical to the NMFS 2018 criteria, only the nomenclature has changed (Southall, et al., 2019; National Marine Fisheries Service, 2018).

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[5] TTS/PTS. A temporary/permanent change in hearing sensitivity caused by acoustic stimuli.

Were relevant we might use the thresholds for behavioural disruption as set by NOAA fisheries[6]. These are 120 dB RMS[7] for continuous noise and 160 dB SPL[8] for impulsive noise.

The hearing groups from the Southall 2019 and the NMFS 2018 guidance were specified by collating available information on marine mammal hearing and generalising their hearing sensitivity into representative groups. This grouping represents a significant research effort and are reviewed by the leading experts (academic, industrial and conservation) on the topic. Because of the large amount of work this represents and the widespread acceptance of the method, the thresholds and the methodology associated, have become de-facto standards for assessing noise impact on marine mammals and represents best available knowledge and practise.

Along with weighting curves, similar in function to the human dB(C) curves, a set of thresholds for hearing impact and injury is associated with the framework and allows for conversion of threshold exceedance into ranges with risk of impact. E.g. we might see that the PW group (true seals) has a risk of PTS at ranges shorter than 50 meters, and a risk of TTS at ranges shorter than 200 meters.

All marine mammal species are covered by the hearing groups and a full list of species in the different groups can be found in the "Marine Mammal Noise Exposure Criteria: Updated Scientific Recommendations for Residual Hearing Effects" (Southall, et al., 2019), but in general the groups cover the following species:

Table 5. Summary of Southall 2019 thresholds and groups with species examples. For full species list see source (National Marine Fisheries Service, 2018; Southall, et al., 2019)

Hearing group	Species examples	Non-impulsive TTS/PTS threshold [$L_{E\text{-}24\ hours}$]	Impulsive TTS/PTS threshold [$L_{E\text{-}24\ hours}$]	Impulsive TTS/PTS threshold [L_p]
PW	Harbour seal, Grey seal	181/201	170/185	212/218
OW	Otters	199/219	188/203	226/232
LF	Minke whale, Humpback whale	179/199	168/183	213/219
HF	Sperm whale, Common dolphin, Bottlenose dolphin, Killer Whale, Risso's dolphin, Pilot whales	178/198	170/185	224/230
VHF	Porpoises, Hourglass Dolphin	153/173	140/155	196/202

It's important to note that the assessment is thus based on the received level of receptors with the above-described auditory sensitivity and not based on the sensitivity of the individual species.

5.3 Fishes etc.

Impacts of noise on fishes is less well established than for marine mammals, but a review from 2014 (Popper, et al., 2014) provides guidelines on exposure limits for fish and turtles. The report does not

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[6] Available from: https://archive.fisheries.noaa.gov/wcr/protected_species/marine_mammals/threshold_guidance.html

[7] Here taken as meaning "SPL"

[8] Assumed to be SPL of 90 % of energy in one impulse or SPL of total duration (L_{EQ}).

directly use the PTS nomenclature (as above for mammals) as many fish have the capacity to repair structural damage to their ear, and even structural damage then cannot be said to be "permanent".

We use "PTS" here to cover the categories "Mortality and potential mortal injury" and "Recoverable injury".

Note that we use the impulsive limits from piling for all impulsive sources as the information for explosions is rather less well documented (and limits are significantly higher).

TTS is directly used in the report, and we use it in the same way here.

Table 6. Overview of Impact piling thresholds from (Popper, et al., 2014) (Table 7.3 in report). We use these for all impulsive noise, even though explosion have separate thresholds (Table 7.2 in report)).

Hearing group	Species examples	Impulsive TTS/PTS threshold [$L_{E\text{-}24\ hours}$]	Impulsive TTS/PTS threshold [L_p]
P* (Fish with no swim bladder)	Sharks, Rays	186/216	TTS not specified/213
P- (Fish with swim-bladder, but not involved in hearing)	Salmon, Trout, Cod, Herring	186/203	TTS not specified/207
P+ (swim-bladder used in hearing)	Carp, Catfish	186/203	TTS not specified/207

5.4 Threshold Interpretation

5.4.1 THRESHOLD TYPES

The three threshold types refer to different ways that sound can affect the hearing of an animal and are ***important to keep in mind*** when evaluating the results of this report:

5.4.1.1 *Non-impulsive, $L_{E\text{-}24\ hours}$*

The threshold, over which an effect (TTS/PTS) occurs, taking into account ***continuous***[9] sound received by the animal over a typical 24-hour period as sound exposure, L_E.

When presented as a zone on a map, this refers to the area, within which, an animal would suffer the effect, if it stayed there for 24 hours (or the full duration of the activity or as otherwise specified). We thus identify areas given by this limit as areas of TTS-**risk** or PTS-**risk** respectively, i.e., an animal within the area has a risk of suffering from either TTS or PTS within the zone.
Alternatively this can be thought of as the total sound-dose limit over 24 hours.
Weightings are applied for non-impulsive L_E (for mammals only[10]).

5.4.1.2 *Impulsive, $L_{E\text{-}24\ hours}$*

The threshold, over which an effect (TTS/PTS) occurs, taking into account ***impulsive*** sound received by the animal over a typical 24-hour period as sound exposure, L_E.
When presented as a zone on a map, this refers to the area, within which, an animal would suffer the effect, if it stayed there for 24 hours (or the full duration of the activity or as otherwise specified). We thus identify areas given by this limit as areas of TTS-**risk** or PTS-**risk** respectively, i.e., an animal within the area has a risk of suffering from either TTS or PTS within this zone.
Alternatively this can be thought of as the total sound-dose limit over 24 hours.

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[9] Please see (National Marine Fisheries Service, 2018) for definitions of "non-impulsive" and "impulsive". For quick reference, if a sound is shorter than 1 second and is clearly intermittent in nature, it is impulsive – otherwise, it's continuous.

[10] When assessing for fish groups levels are not weighted.

5.4.1.2.1 Impulsive $L_{E\ \text{single impulse}}$ / $L_{E\ \#\ \text{impulses}}$

It is sometimes useful to assess the impact of a single/a number of impulse(s). When we do this, we will refer to it as "LE single impulse / LE # impulses".
Like for the Lp, when single-impulse LE is presented as an impact zone, this refers to the area, within which, an animal would suffer the effect acutely/instantly.

Weightings are applied for Impulsive L_E (for mammals only).

5.4.1.3 Impulsive, L_p

The threshold over which an effect (TTS/PTS) occurs, taking into account ***impulsive*** sound received by the animal at any instant as maximal peak pressure.
When presented as a zone on a map, this refers to the area, within which, an animal would suffer the effect acutely/instantly and from just one exposure.
Weightings are ***not*** applied for Impulsive L_P.

5.4.2 MASKING

Levels that are not over threshold can still cause significant impact, if that noise makes foraging, navigation or communication harder due to masking or where biologically relevant sounds are "drowned out" by the anthropogenic noise. Continuous noise is more likely than impulsive noise to cause this form of impact.

5.4.3 DISPERSAL

Many animals can recognise sounds and might be dispersed from an area at noise levels well below TTS limits. Quantifying a level of dispersal from desk-spaced studies is very challenging and not done here.

6 CONCLUSION

Dredging

The noise from dredging, while presenting a significant PTS risk to ranges >100 m for the LF and VHF groups, this is only for animals staying close to the activity for extended periods. There is no acute risk of noise related injury related to the dredging, and animals have time to swim away.

Vibro piling

Even prolonged exposure to vibro piling at close range (<100 m) carries little to no auditory risk for the animals assessed.

7 RESULTS SUMMARY

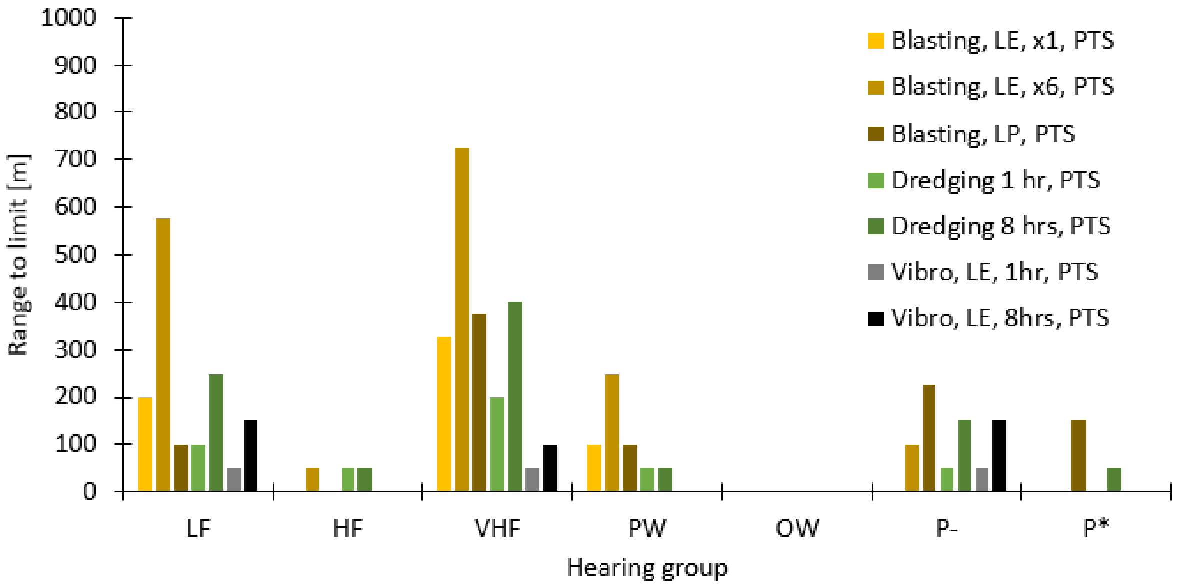
Full results and all maps can be found in APPENDIX E – Results

7.1 Overview

Table 7. Overview of maximal ranges to limits [m]. In bold where PTS is over 500m. Note that where P- ranges exceed ~500 meter there is an overlap with the fish farm north of the pier.

Activity	Blasting						Dredging				Vibro piling			
Dose/type	1 blast L_E		6 blasts L_E		Peak pressure L_P		1 hr L_E		8 hrs L_E		1 hr L_E		8 hrs L_E	
Hearing group	TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS
LF	1500	200	3850	**575**	150	100	875	100	2900	250	550	50	1325	150
HF	100	<50	225	50	75	<50	100	50	250	50	<50	<50	50	<50
VHF	1500	325	3600	**725**	625	375	950	200	2125	400	225	50	625	100
PW	600	100	1825	250	150	100	225	50	725	50	100	<50	275	<50
OW	50	<50	225	<50	75	<50	50	<50	75	<50	<50	<50	<50	<50
P-	325	<50	850	100	<50	225	325	50	1100	150	350	50	1175	150
P*	325	<50	850	<50	<50	150	325	<50	1100	50	350	<50	1175	<50

Figure 18. Overview of PTS risk ranges, note that both LF and VHF groups have PTS range > 500 m for Blasting



7.2 Blasting

We assume all daily blasts take place during a short time-window (< 1 min) so while the peak pressure does not increase with additional blasts the cumulative exposure will be from 4 to 6 blasts, with no opportunity to swim away. PTS ranges for LF (baleen whales) and VHF (porpoises) groups are > 500 m, with TTS ranges > 3.5 km for these two groups. Remaining groups have PTS ranges well below 500 m, with the PW group (seals) having a PTS risk range of 250 m.

Figure 19. TTS and PTS risk ranges for all groups.

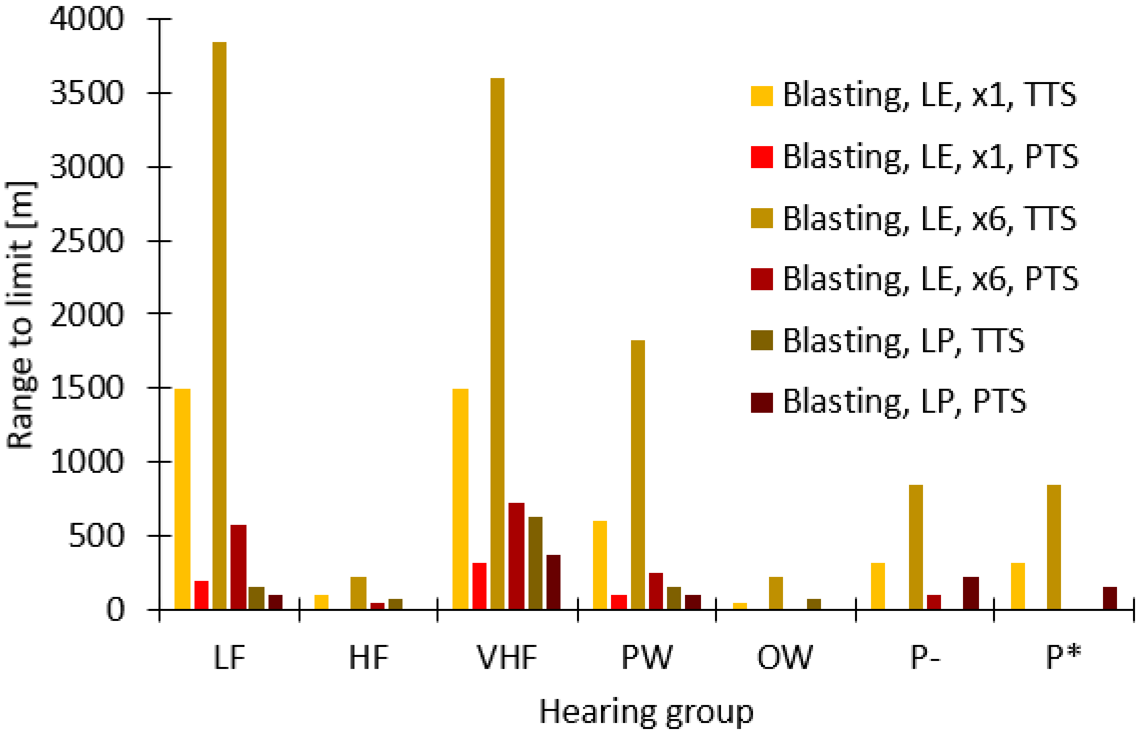
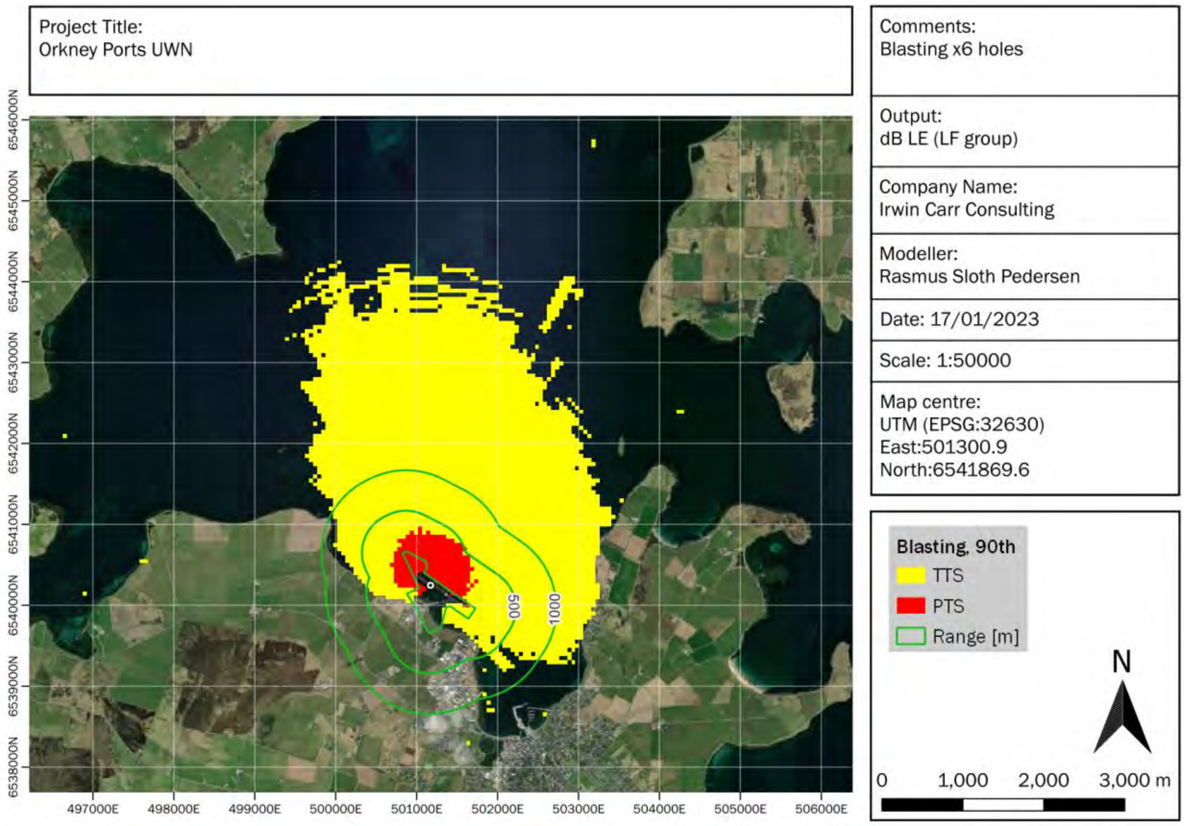


Figure 20. Blasting (6 blasts) with risk zones for the LF group.


Project Title:
Orkney Ports UWN

Comments:
Blasting x6 holes

Output:
dB LE (LF group)

Company Name:
Irwin Carr Consulting

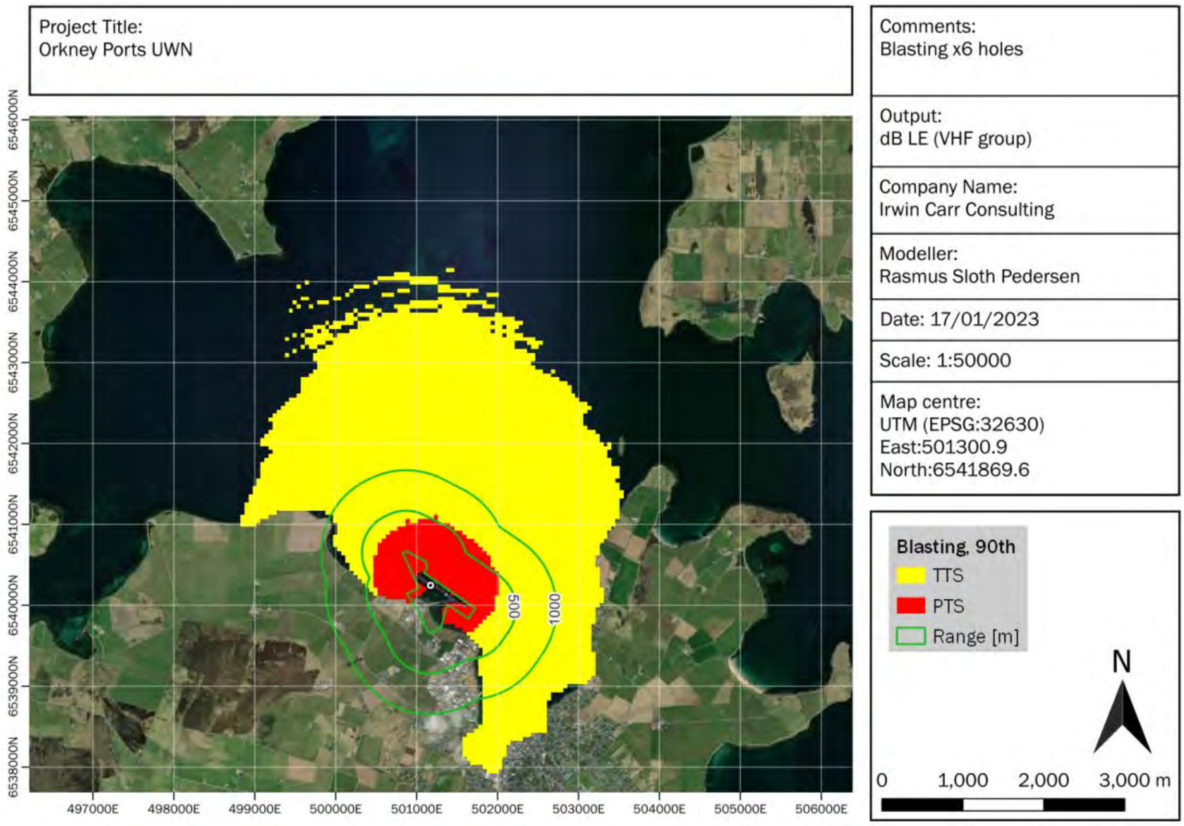
Modeller:
Rasmus Sloth Pedersen

Date: 17/01/2023

Scale: 1:50000

Map centre:
UTM (EPSG:32630)
East:501300.9
North:6541869.6

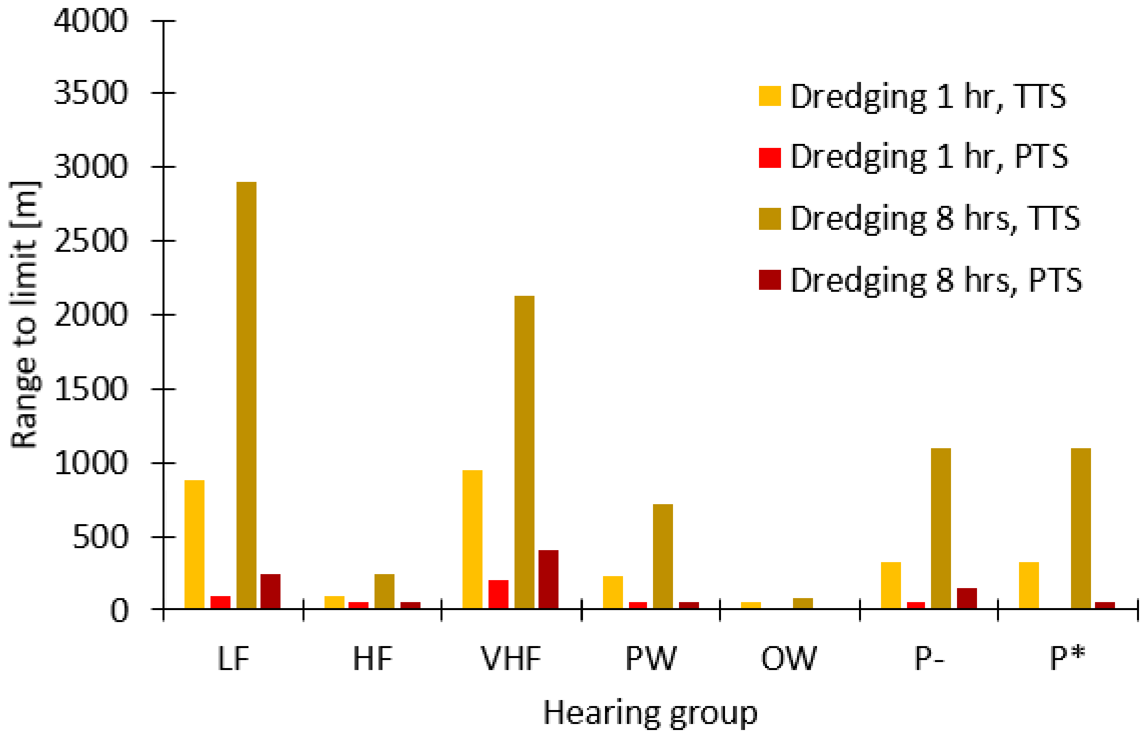
Figure 21. Blasting (6 blasts) with risk zones for the VHF group.



7.3 Dredging

While exposure to 8 hours of dredging has significant risk ranges (> 100 m) for 3 hearing groups: LF (baleen whales), VHF (porpoises) and P- (Fish with swim bladder), but only after prolonged exposure. The relatively low (compared to limits) source level of the dredging means that there is not acute risk from noise and animals have time to swim away.

Figure 22. TTS and PTS risk ranges for all groups.

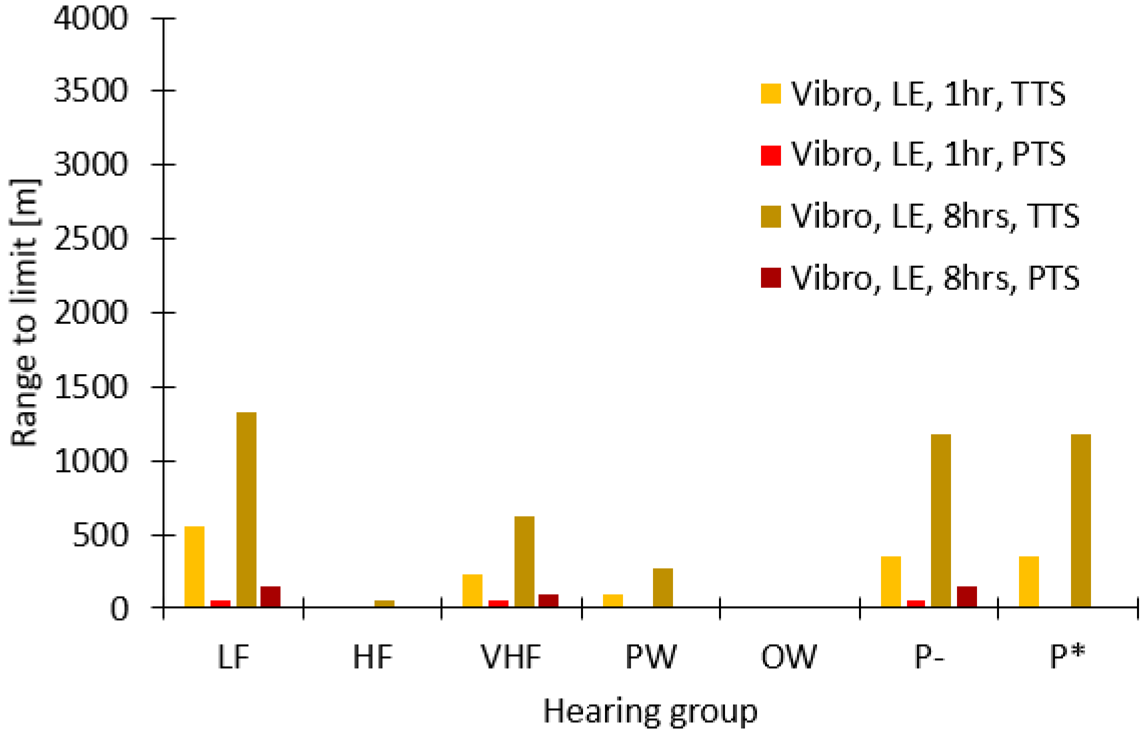


7.4 Vibro piling

Note that we have not assessed LP for vibration piling as the peak level is below limits for all hearing groups.

Vibro piling has short risk ranges for PTS for all hearing groups, and only long exposure (> 1 hr) leads to risk ranges over 50 m.

Figure 23. TTS and PTS risk ranges for all groups.



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APPENDIX A - DBSEA

A summary of dBSea's models in standard scenarios can be found in the document (online):
http://www.dbsea.co.uk/media/30782/dBSea-Benchmark-Testing.pdf
(also see Figure 26, p. 32 for one example).

All solvers in dBSea are based on Jensen et al. 2011 (Jensen, Kuperman, Porter, & Schmidt, 2011)

dBSea has four primary models of calculation:

- **Range dependent Parabolic Equation model - dBSeaPE**
  dBSeaPE uses a split-step, wide angle parabolic equation method. It uses either Greene's approximation or several Padé terms (as set by user) to get very wide propagation with low phase error.

  dBSeaPE is best suited to deeper scenarios (>50 m) or where sediment interaction is not dominant relative to sound speed profile. The model is very efficient for low frequencies and only suffers a small efficiency penalty for higher frequencies.

  dBSeaPE will generally be used for deeper/long range scenarios in the frequency interval 10-1000 Hz.
- **Range dependent Normal Modes model - dBSeaModes**
  dBSeaModes is especially suited to shallower and sediment dependent scenarios and will typically be used where water is shallower than 50 m and depth changes are a large proportion of the total depth, or where sediment effects are thought to play a significant role. dBSeaModes incurs a significant efficiency-penalty at high frequencies and will normally be used in the frequency range 10-1000 Hz.
- **Ray tracing**
  dBSea uses a Gaussian raytracing method, dBSeaRay, to calculate transmission losses for higher frequencies (scenario dependent, but normally from 500 Hz). dBSeaRay compares favourably with the opensource BELLHOP model, in that it is accurate to lower frequencies and agrees well with PE and NM models.
- **Full waveform propagation**
  dBSeaRay also supports full waveform propagation in the frequency range 10 Hz to 168 kHz (limited by the waveform sample rate). Used in this way dBSeaRay takes into account all scenario range dependence (as models above) as well as the arrival time, phase information and transmission loss of all significant paths to any number of receivers in the scenario (the results grid).

General notes:

- dBSea is an "Nx2D" solver, meaning it models transmission losses in "N" number of vertical radial slices from the source (Figure 25, p. 31). There is no backwards propagation towards the source, and no sideways reflection/refraction (We're testing dBSea with full 3D solvers currently).

- dBSea models the sediment propagation only for compressional waves, not for shear waves. This generally means that the transmission loss will be slightly underestimated as no energy is transferred into shear waves, and also means that dBSeaRay does not propagate into the sediment, but relies on a complex reflection coefficient (calculated from the sediment layers) to calculate the reflection/refraction properties of the sediment. Given that dBSeaRay is generally only used for higher frequencies, this has very little practical effect, as higher frequencies will only interact weakly with deeper layers of the sediment.

- The individual sources in a scenario are modelled radially (radial coordinates) from the source at several depths. In post-processing levels are transferred to a cartesian "results grid". This results grid stores levels from all sources so that the cumulative level at any point in the scenario can be investigated immediately.

- Levels can be, and are often post-processed to apply a conservative margin and smooth results (Figure 24, p. 31). Radial smoothing (triangular kernel of variable width) is carried out to mitigate modelling artefacts arising from low environment sampling density or chance occurrences. Levels are often made to decrease monotonically from the source to make general trends more visible and decrease the risk of misinterpreting impact ranges.

- When refereeing to a level at a certain range, this usually refers to the greatest level at any depth at that range (unless specifically mentioned otherwise).

Figure 24. Post-processing to eliminate artefacts and ease interpretation. Level are radially smoothed by default, and are made to be monotonically decreasing with increasing range from the source.

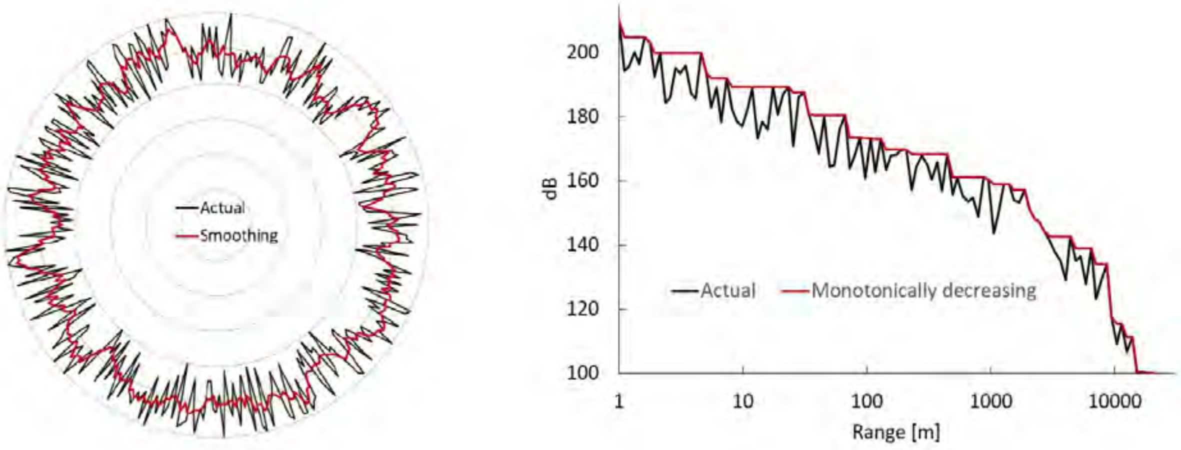


Figure 25. Low resolution schematic of the dBSea modelling space. Source transmission loss is modelled radially from the sources at a number of depths. Results are extracted from a "square" 3D grid that hold cumulative levels from all sources in the scenario.

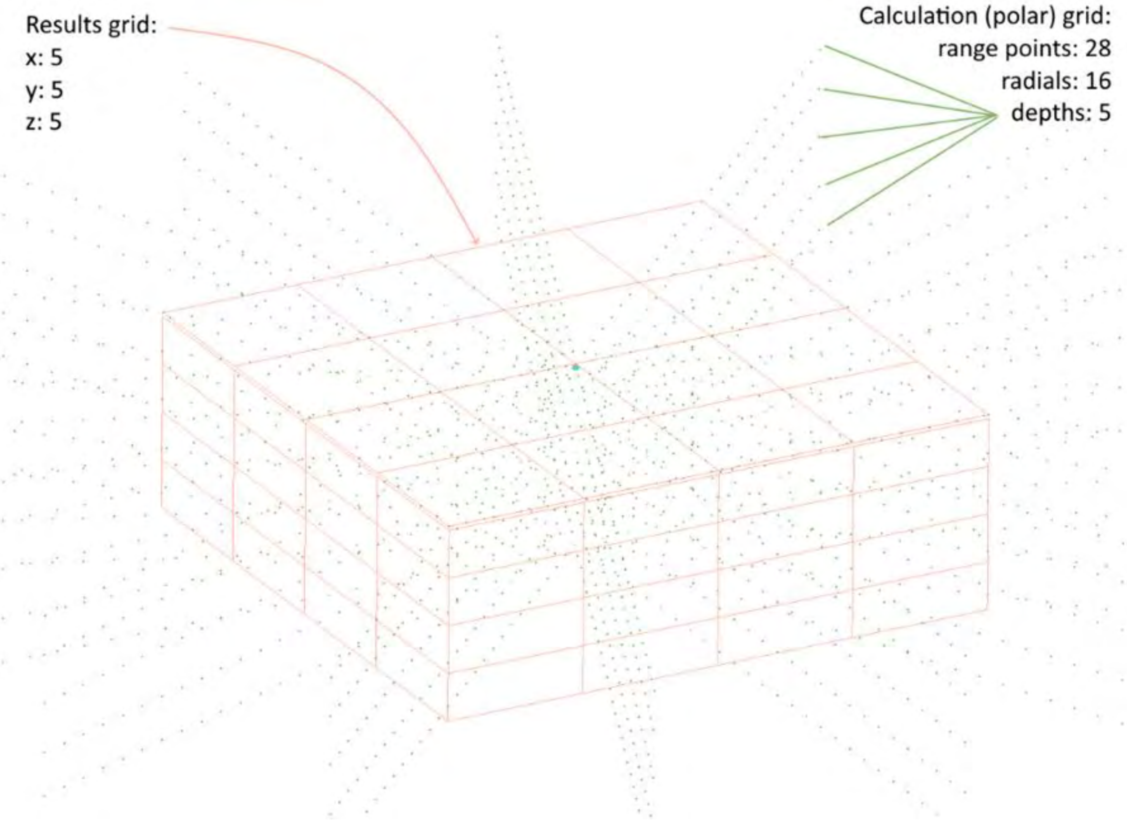
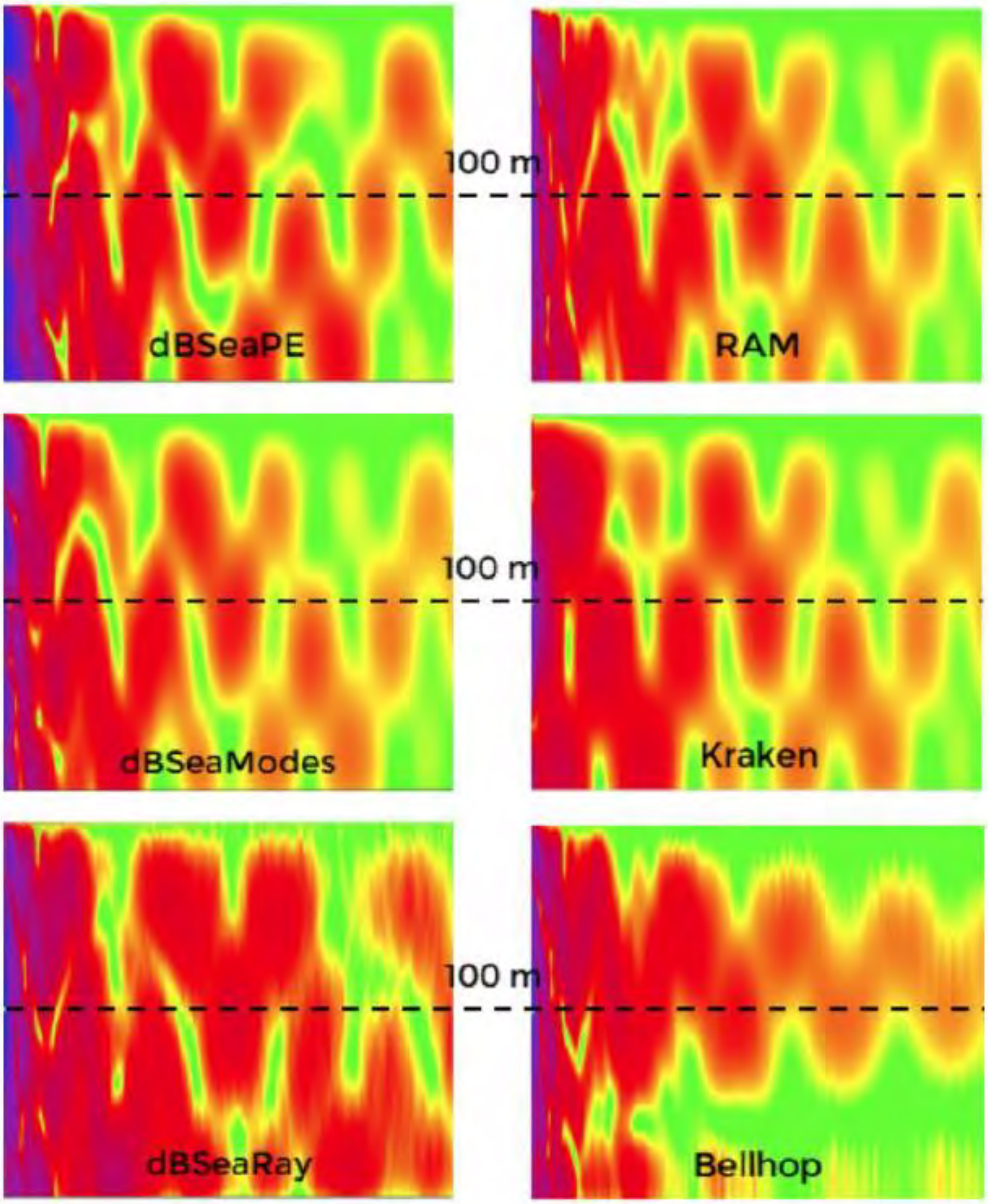


Figure 26. the "Pekeris" standard problem, a low frequency problem. Note that due to sediment effects, neither dBSeaRay nor Bellhop should be relied upon for low frequency problems, and are only include for completeness.



APPENDIX B – UNDERWATER ACOUSTICS BASICS

Sound Speed

Water is much harder to compress than air, and a soundspeed of 1500 m/s is often used as a standard soundspeed in water[11] much as 340 m/s is in air. Soundspeed is given by the following equation:

$$c = \frac{Z}{\rho}$$

$$Soundspeed\ [m/s] = \frac{Acoustic\ impedance\ \left[\frac{kg}{m^2 \cdot s}\right]}{Specific\ density\ [kg/m^3]}$$

Because changes to pressure, salinity and temperature occur with changes in depth, the specific density and acoustic impedance of water changes with depth, and thus the soundspeed changes as well.

The soundspeed profile is quite important in sound propagation, as refraction (changes in propagation angle) will occur when sound moves between layers of water with varying sound speed. This change is quantified in “Snell’s Law” and results in sound being “bent” towards the depth of minimal soundspeed. These effects can lead to profoundly inhomogeneous sound fields and SOFAR channels.

The same relationships are valid in the sediment, though sediments commonly have soundspeeds higher than water. Soundspeeds from 1700 m/s (fine sand/silt) to 2500 m/s (gravel) are common for non-solid sediments, with solid sediments (rocks) having much higher soundspeeds 2800 m/s (Calcarenite) to 6000 m/s (some granite).

Spreading loss

Most of the propagation loss (loss in dB from source to receiver, “PL”) that occurs initially is governed by “spreading loss”. It is the simple “thinning out” of acoustic energy as it spreads away from the source, usually in all directions – spherically.

For a sound source in an unbound medium the initial PL will be dominated by spherical PL:

$$Received\ level = Source\ level_{at\ reference\ range} - 20 \cdot \log_{10}\left(\frac{range}{reference\ range}\right)$$

This means a reduction in received level of 6 dB per doubling of distance and explains the rapid reduction in received levels often seen close to the source, e.g.: with a reference range of 1 m, at 16 meters range, there has been 4 doublings of distance, and thus 24 dB loss (4×6 dB).

At longer ranges the medium is no longer unbounded. We reach ranges where the sound has interacted with the surface (near perfect acoustic reflector) or the seabed (lossy acoustic reflector). Also, at greater ranges a doubling of distance is no longer trivial as the PL from spherical spreading loss from 500 m to 1000 m is also just 6 dB.

Sound Channels and Wave guides

In bounded mediums where the sound energy is confined to cylindrical spreading, the PL (ignoring absorption) is often well-characterised by:

$$Received\ level = Source\ level_{at\ reference\ range} - 10 \cdot \log_{10}\left(\frac{range}{reference\ range}\right)$$

This means a reduction of received level of 3 dB per doubling of distance. Depending on the sediment this kind of “waveguide” can sustain efficient transmission of sound over long ranges, provided the sediment is acoustically hard and there is low absorption (such as is the case for low frequencies or in low salinity).

In absence of a bounding from the surface or the seabed, a soundspeed profile with a clear low-speed region, surrounded by higher soundspeeds can act a sound channel, by focusing the sound towards a single depth (with lower soundspeed), limiting the PL from spherical to cylindrical (a SOFAR channel is formed).

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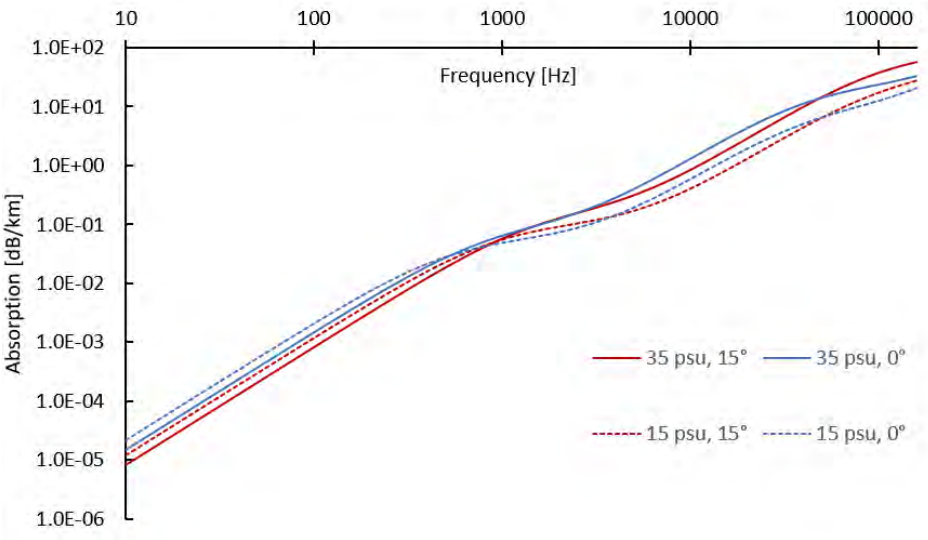
[11] Varies from 1450 m/s at 0° to 1550 m/s at 30° at salinity of 35 psu.

Absorption

Besides the “thinning out” of the sound energy as described above, the sound is also dissipated into heat by the way the pressure changes interact with water, molecules and particles in its path. This absorption is mostly governed by the concentration of boric acid and magnesium sulphate and is very dependent on the frequency, with lower frequencies, <1 kHz, experiencing almost no absorption, while high frequencies, > 10 kHz, can be attenuated by over 10 dB / km.

Figure 27. Absorption comparison at salinities of 35 psu & 15 psu and temperatures of 0° and 15°. Both scales are logarithmic. Note how increased salinity increases high-frequency absorption (solid v dashed lines), while a decrease in temperature increases absorption at lower frequencies (red v blue lines).



Small bubbles, wind or wave induced, will further attenuate especially the high frequencies, but as modelling is often done to estimate a worst-reasonable case, or for weather sensitive activities, fair weather with little wind and waves are assumed, thus ignoring this attenuation effect.

Sediment

Depending on the incident angle of the sound, the frequency and the acoustic properties of the sediment, sound can either mostly penetrate the sediment or mostly be reflected by it.

In shallow areas with soft sediment (acoustically similar to water), it is typical to find that close to the source, at high incidence angles and at low frequencies (<250 Hz) the sound will penetrate into the sediment and dissipate there, leading to very high transmission losses for these frequencies. This effect coupled with the high absorption at high frequencies often leads to the soundscape being dominated by frequencies from a few hundred hertz to a few thousand hertz. In deeper water, or with an upward refracting soundspeed profile, low frequencies will tend to dominate the soundscape away from sound sources, as there is no efficient mechanism for attenuating them.

A “cut-off[12]” frequency, below which, there will be high sediment-associated attenuation can be approximated by:

$$f_{cut-off} = \frac{c_{water}}{4 \cdot D \cdot \sqrt{1 - \left(\frac{c_{water}}{c_{sediment}}\right)^2}}$$

With “C_{water}” and “$C_{sediment}$” being the soundspeed in the water and the sediment respectively, and “D” the local depth (Jensen, Kuperman, Porter, & Schmidt, 2011).

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[12] The cut-off is not an immediate loss of energy in frequencies under this frequency, but rather something like a high pass, 1st-order, Butterworth filter (Audoly, 2020).

In water with lower salinity and less absorption, the soundscape will tend to have a relatively higher content of high frequencies as these are absorbed much less efficiently when the salinity is lower.

Sound transmission Across Interfaces

Sound waves are reflected and refracted (Snell's law) as they travel through interfaces. Also, depending on acoustic impedance and interface angles only a proportion of the incident acoustic energy is transmitted through that interface (the rest is reflected).

In the following: W: Watt; Pa: Pascal; s: second; m: metre; N: Newton; J: Joule; θ: angle; v: soundspeed; Z: acoustic impedance; p: pressure from ambient;

Snell's law:

$$\frac{\sin\theta_{in}}{\sin\theta_{out}} = \frac{v_{in}}{v_{out}}$$

- rearranged to give transmission angle from incidence angle and soundspeeds:

$$\sin^{-1}\left(\frac{\sin\theta_{in}}{\frac{v_{in}}{v_{out}}}\right) = \theta_{out}$$

Transmission fraction of sound pressure for plane waves (part of the Fresnel equations):

$$\frac{p_{out}}{p_{in}} = \frac{2 \cdot Z_{out} \cdot \cos\theta_{in}}{Z_{out} \cdot \cos\theta_{in} + Z_{in} \cdot \cos\theta_{out}}$$

Reflection fraction of sound pressure for plane waves (part of the Fresnel equations):

$$\frac{p_{out}}{p_{in}} = \frac{Z_{out} \cdot \cos\theta_{in} - Z_{in} \cdot \cos\theta_{out}}{Z_{out} \cdot \cos\theta_{in} + Z_{in} \cdot \cos\theta_{out}}$$

It follows from these relations that for transmission from an acoustically relatively slow medium like water to an acoustically faster medium here exists an incident angle above which there is total reflection, and thus no transmission of acoustic energy through the interface (real interfaces are rugged and lumpy, and perfect reflection is not realistic).

For the water/sediment interface presented here (sediment is sand with a soundspeed of 2000 m/s) this occurs at 0.84 radians (~48.5 degrees) from normal incidence.

The fraction of pressure transmission from water (soundspeed 1500 m/s) to sediment (2000 m/s) is around 146 % at normal incidence and drops as the incidence angle increases away from normal, much faster for water-to-sediment than for sediment-to-water.

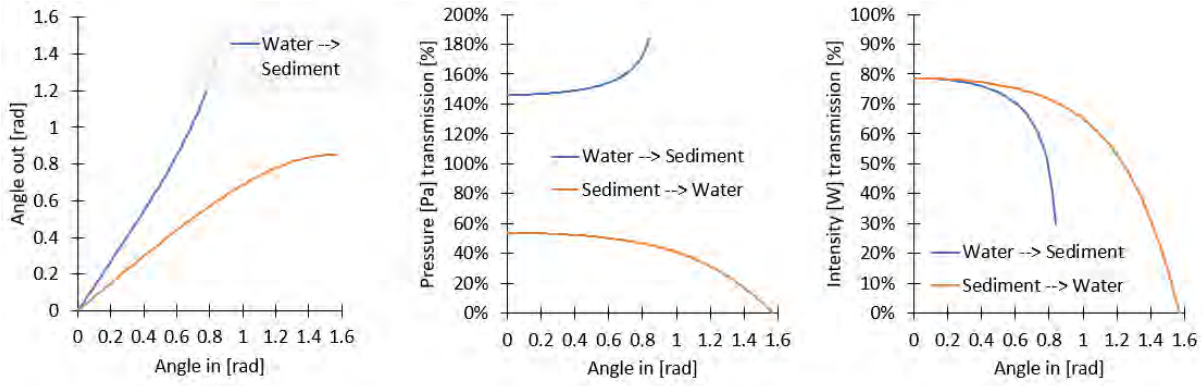
While it may seem counter-intuitive that pressure can increase after transmission over an interface, remember that the energy in the sound is a function of pressure *and* acoustic impedance:

$$I = \frac{p^2}{Z}$$

$$With\ units: [W] = \frac{[Pa]^2}{\left[\frac{Pa \cdot s}{m^3}\right]} = \frac{\frac{N^2}{m^4}}{\frac{\frac{N}{m^2} \cdot s}{m^3}} = \frac{N^2 \cdot m^3}{m^4 \cdot \frac{N}{m^2} \cdot s} = \frac{N}{m \cdot m^{-2} \cdot s} = \frac{J \cdot m}{m^{-1} \cdot s} = \frac{J}{s} = W$$

Thus, if the transmitted intensity fraction is 80 % then the reflected intensity is 20 %; there is energy conservation.

Figure 28. Transmission angles [radians] and fractions as function of incident angle between water and sediment (sand). Note that total reflection from water to sediment occurs around incident angle of 0.84 [rad] (48.5 degrees), meaning there is no transmission of sound at greater incidence angles.



Simplified Propagation Loss Model

Taking all the above into account we can construct a simplified model, that will give a good indication of the expected propagation loss (PL) in scenarios of constant depth:

$$PL = \left\{ \begin{matrix} r < D \ : & -20 \cdot \log_{10}\left(\frac{r}{r_0}\right) \\ r > D \ : & -20 \cdot \log_{10}\left(\frac{D}{r_0}\right) - 10 \cdot \log_{10}\left(\frac{D}{r_0}\right) \end{matrix} \right\} - \alpha(f) \cdot r - l(f) \cdot r$$

Where:

- “r” is horizontal range from source.
- “D” depth at source.
- “r_0” the reference range of the source (often 1 m).
- “f” the frequency,
- “l” the frequency specific leakage loss to the sediment.
- “α” the frequency specific absorption.

Sound Level Units

All references to sound pressure levels, peak pressure levels and sound exposure levels refer to a logarithmic ratio between a reported/measured pressure or exposure and a reference pressure or exposure. As an example, a level of 220 L_p (decibel zero-to-peak) is equal to a peak pressure of 100000 Pascals (Pa) over ambient pressure, while 120 L_p is equal to 1 Pa over ambient pressure.

To avoid dealing with these large numbers as pascals (as a linear scale), they are converted to a decibel ratio (Table 1 for definitions). Besides compressing large numbers to a smaller scale this also corresponds better to how animals are thought to perceive sound, namely as relative steps. This means that an increase from 1 to 2 Pa *sounds like* the same increase as from 100 to 200 Pa, even though the first step was only 1 Pa, while the second was 100 Pa. This is better reflected in a logarithmic scale based on ratios, where both steps are equal, here 3 dB.

However, while dBs are practical, they can be hard to compare between studies, due to vague definitions, and so we have adopted the standards set by ISO 18405-2017 (Table 1 below).

For ease of reference please see following overview for unit definition.

Table 8: Definitions.

Unit	Definition	Comments
SPL (dB$_{\text{RMS}}$) ISO 18405- 2017: 3.2.1.1	$SPL = 10 \cdot Log_{10}\left(\frac{\frac{1}{t_2 - t_1} \cdot \int_{t_1}^{t_2} p(t)^2 dt}{1 \cdot 10^{-12} Pa}\right)$	Functionally equivalent to deprecated $20 \cdot Log_{10}\left(\frac{RMS}{1 \cdot 10^{-6} Pa}\right)$
L$_{\text{p}}$ (dB$_{\text{z-p}}$) ISO 18405- 2017: 3.2.2.1	$L_p = 20 \cdot Log_{10}\left(\frac{Pa_{max}}{1 \cdot 10^{-6} Pa}\right)$	This assumes that Pa_{max} is equal or greater than $\sqrt{{Pa_{min}}^2}$
L$_{\text{p-p}}$ (dB$_{\text{p-p}}$)	$L_{p-p} = 20 \cdot Log_{10}\left(\frac{Pa_{max} - Pa_{min}}{1 \cdot 10^{-6} Pa}\right)$	Often[13] equivalent to $L_P + 6.02\ dB$
L$_{\text{E}}$ (dB$_{\text{SEL}}$) ISO 18405- 2017: 3.2.1.5	$L_E = 10 \cdot Log_{10}\left(\frac{\int_{t_1}^{t_2} p(t)^2 dt}{1 \cdot 10^{-12} Pa}\right)$	For continuous sound this is equivalent to $SPL + 10 \cdot Log_{10}(t_2 - t_1)$ “t” is seconds

Unless otherwise stated SPL has an averaging period of 1 second, and L$_{\text{E}}$ for the duration of the specified event, sometimes indicated as L$_{\text{E-“time”}}$ or L$_{\text{E-single blow}}$.

If the averaging period for SPL is equal to the total even duration, then SPL is equal to “Leq” the “equivalent constant level”.

When source levels are presented, the same units are used, and it is implicit that all source levels are given as if recorded 1 m from an omnidirectional mono-point source, unless otherwise specified.

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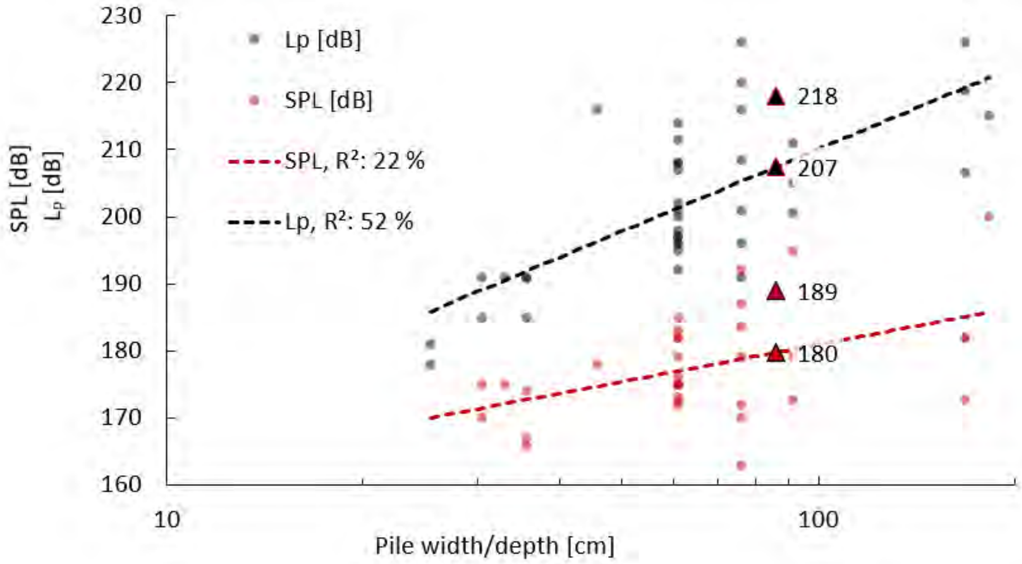
[13] If maximum pulse rarefaction is below ambient pressure and compression and rarefaction phases are of equal size.

APPENDIX C – SOURCE MODELS

We only have a few recordings (50) from vibration piling and have no dedicated source model for this type of piling. Instead, we rely on published recorded levels as from CalTrans (CalTrans, 2015).

Figure 29. Basis of vibro piling broad band source level as a function of pile size.



Given the low confidence we have in this approach (low R^2 values) we use the 90th percentile level as the broadband source level. L_P is estimated to be 218 dB and SPL 189 dB. The frequency content is assumed to be identical to that of the impact piling.

Table 9. Decidecade band levels of sources.

Band centre frequency [Hz]	Dredging, Mean (broadband: 182) [SPL]	Dredging, 90th percentile (broadband: 192) [SPL]	Drilling, Mean (broadband: 138) [SPL]	Drilling, 90th percentile (broadband: 156) [SPL]	Blasting, 15 kg (broadband: 220) [LE]	Blasting, 20 kg (broadband: 222) [LE]	Vibro, Mean (broadband: 180) [SPL]	Vibro, 90th percentile (broadband: 189) [SPL]
12.5	162	165	127	142	206	208	159	169
16	163	166	126	139	206	208	159	169
20	164	167	124	139	206	208	160	169
25	165	170	123	138	206	208	160	169
31.5	168	177	125	139	206	208	160	170
40	169	180	124	140	206	208	162	171
50	169	178	124	139	206	208	165	174
63	170	178	126	143	206	208	167	176
80	169	180	123	142	206	208	169	178
100	168	179	124	142	206	208	170	179
125	168	178	123	140	206	208	170	180
160	168	178	123	142	206	208	170	179
200	168	177	125	146	206	208	170	179
250	169	178	126	147	206	208	169	179
315	169	178	125	147	206	208	168	177
400	169	177	123	144	206	208	167	176
500	168	178	124	145	206	208	165	175
630	167	175	122	143	206	208	164	173
800	167	174	124	141	206	208	162	171
1000	166	174	125	142	206	208	160	169
1250	165	174	123	142	206	207	158	167

1600	165	174	121	138	206	207	157	166
2000	164	174	120	135	205	206	155	164
2500	163	175	119	134	204	206	153	162
3150	163	175	118	132	204	205	152	161
4000	162	175	118	132	203	204	150	160
5000	162	175	119	133	202	203	149	158
6300	161	175	118	130	201	202	148	157
8000	160	175	117	130	200	201	147	156
10000	159	174	117	129	199	200	145	154
12500	158	173	110	120	198	199	143	152
16000	157	173	109	118	197	198	143	152
20000	156	172	109	119	196	197	142	151
25000	156	171			195	196	141	150
31500	155	171			194	195	140	149
40000	154	170			193	194	139	148
50000	157	174			192	193	138	147
63000	156	173			191	192	137	146
80000	156	173			190	191	136	145
100000	157	172			189	190	135	144
125000	157	166			188	189	134	143
160000	157	166			187	188	133	142

APPENDIX D – MODEL CALIBRATION

Recorded Transmission losses

Scapa

Broadband transmission losses for exposure levels (L_E) show good consistency between measurements and a transmission loss consistent with -14.7 × Log_{10}(range), suggesting a sediment with some ability to reflect sound back into the water column and form a waveguide.

Transmission loss for peak pressure levels (L_P) were near spherical spreading loss which is consistent with a poorly reflecting bottom resulting in little overlap in arrival times for the source impulse.

There was a clear pattern in the transmission losses versus frequency, with higher frequencies experiencing much higher losses, likely due to interaction with a rough sediment resulting in a lot of scattering.

Note that for the bands 50 – 1250 Hz the ambient noise at Scapa was above the source level, while we have tried to compensate for this, those values are still subject to considerable uncertainty (Figure 31, p. 40).

Figure 30. Broadband transmission losses at Scapa. L_P losses follow a near spherical loss pattern while L_E shows a tendency to follow a waveguide with some absorption losses. Thick lines are best fit of logarithmic loss, while thin lines are for loss accounting for the depth at the source. Error bars are expected 95 % of measurements.

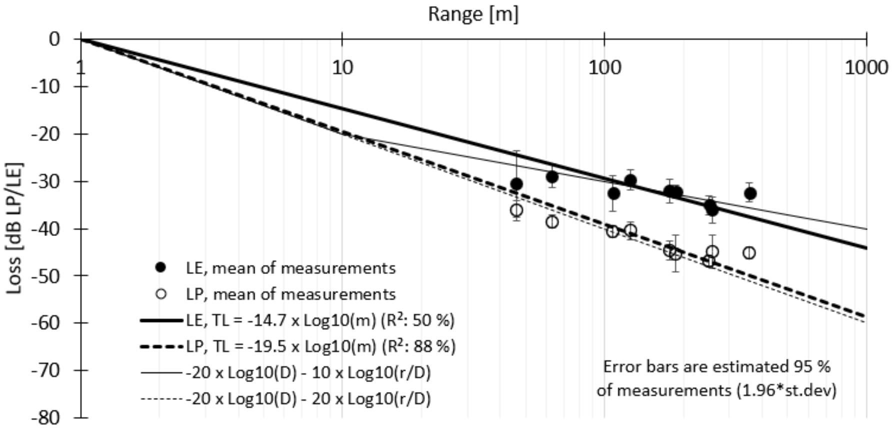
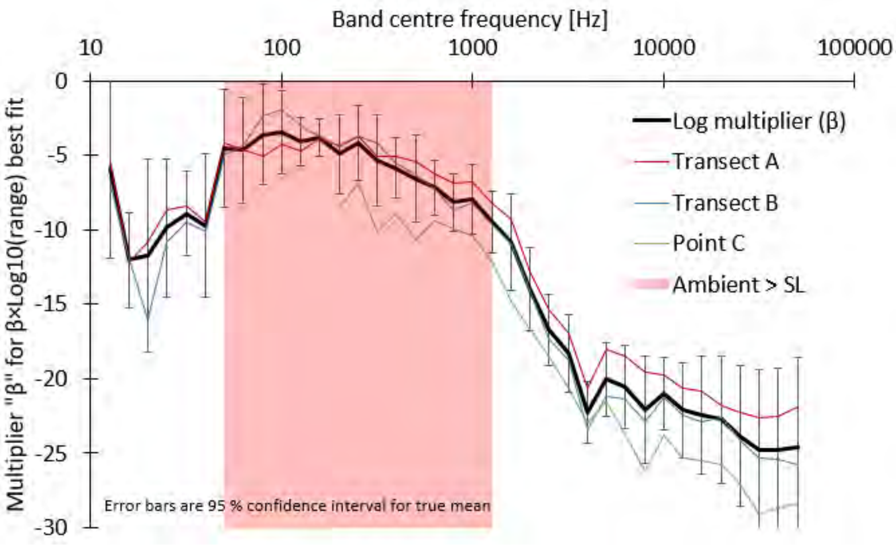


Figure 31. Transmission losses per band shown as the best fit multiplier "β" for a simple logarithmic transmission loss. Error bars are 95 % confidence interval for the true mean. While Transects A & B have some difference, this was not significant at a 10 % level in a t-test. Bands 50 – 1250 Hz have been corrected for contributing ambient noise as ambient noise was near or above recorded levels (red band).



Hatston

Broadband transmission losses for exposure levels (L_E) show good consistency between measurements and a transmission loss consistent with -22.2 × Log_{10}(range), suggesting a highly absorbent sediment with little ability to reflect sound back into the water column and form a waveguide as well as high scattering from a rough seabed.

Transmission loss for LP were close to spherical spreading loss which is consistent with a poorly reflecting bottom resulting in little overlap in arrival times for the source impulse.

There was a clear pattern in the transmission losses versus frequency, with higher frequencies experiencing much higher losses, likely due to interaction with a rough sediment resulting in a lot of scattering.

Figure 32. Broadband transmission losses at Hatston. L_P losses follow a near spherical loss pattern while L_E shows a tendency to follow a waveguide with some absorption losses. Thick lines are best fit of logarithmic loss, while thin lines are for loss accounting for the depth at the source. Error bars are expected 95 % of measurements.

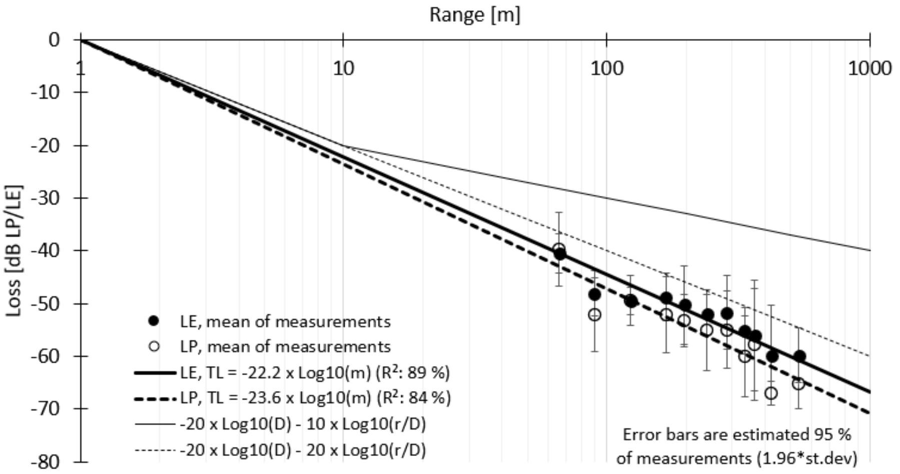
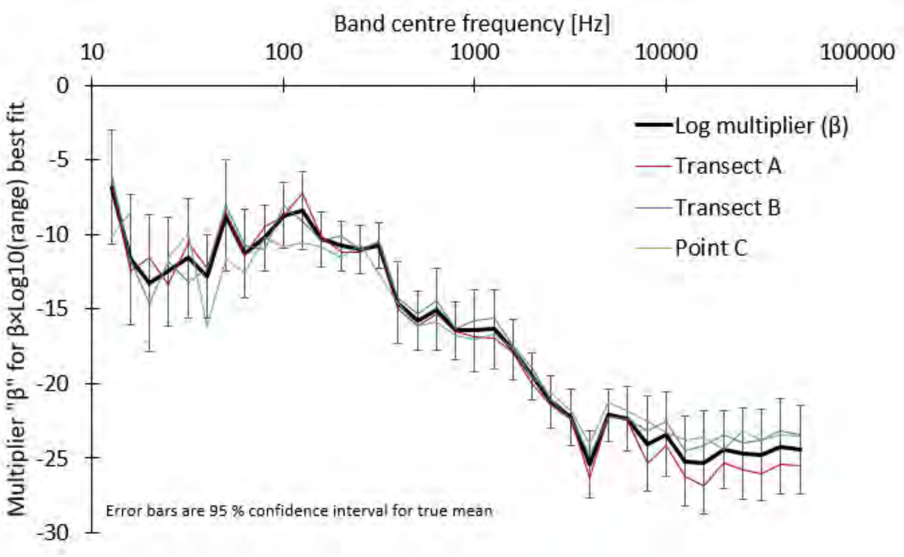


Figure 33. Transmission losses per band shown as the best fit multiplier "β" for a simple logarithmic transmission loss. Error bars are 95 % confidence interval for the true mean. While Transects A & B have some difference, this was not significant at a 10 % level in a t-test.



APPENDIX E – RESULTS

Maps are presented with impact for different hearing groups as summarised here

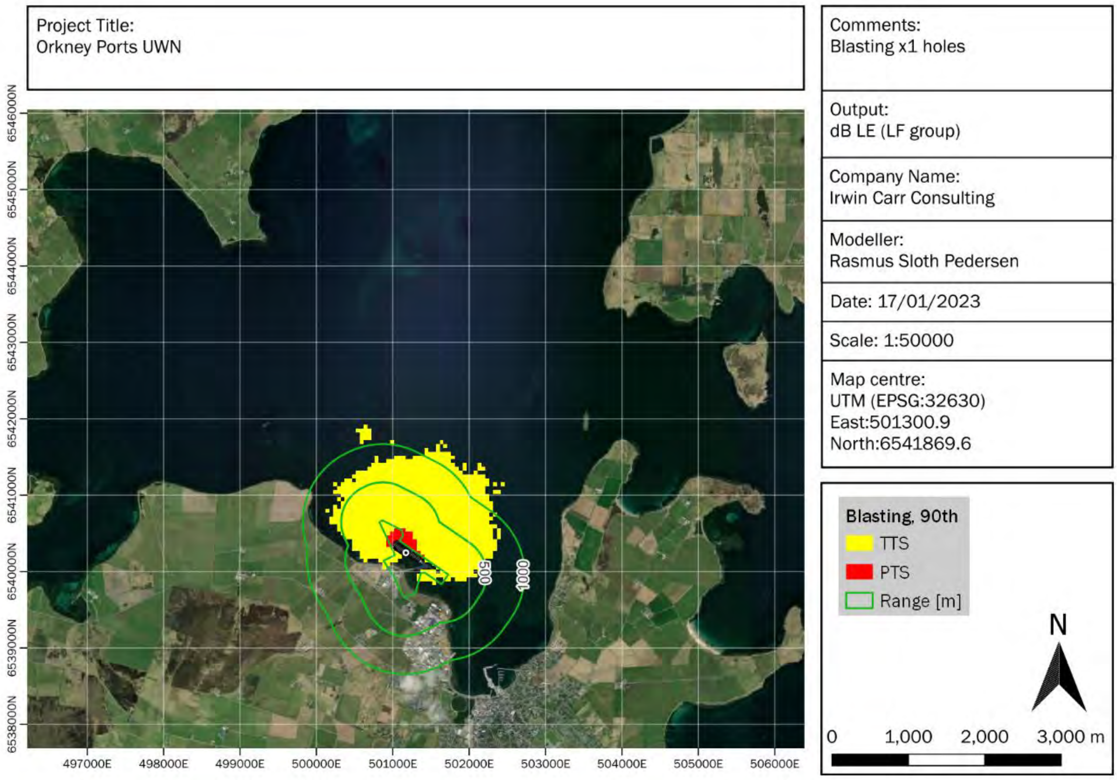
Group	Description	Example species
LF	Low frequency, baleen whales	Mike whale, Fin whale, Blue whale
HF	High frequency, most dolphins	Common dolphin, Risso's dolphin, beaked whales, Bottlenose dolphin, Sperm whale, Killer whale
VHF	Very high frequency, few dolphins and porpoises	Harbour porpoise, Hourglass dolphin
PW	Phocid water, True seals	Harbour seal, Grey seal
OW	Otariid + other water, Fur seals, walruses and aquatic mammals	Walrus, Otter, Polar bear
P-	Fish with swim bladder, not coupled to inner ear	Salmon, Trout, Cod, Herring
P*	Fish with no swim bladder	Sharks and rays

Blasting

Max daily blast is 6. Maps are here shown for 1 and 6 blasts.

Blasting LE

Figure 34. Blasting, LE, x1, LF group


Project Title:
Orkney Ports UWN

Comments:
Blasting x1 holes

Output:
dB LE (LF group)

Company Name:
Irwin Carr Consulting

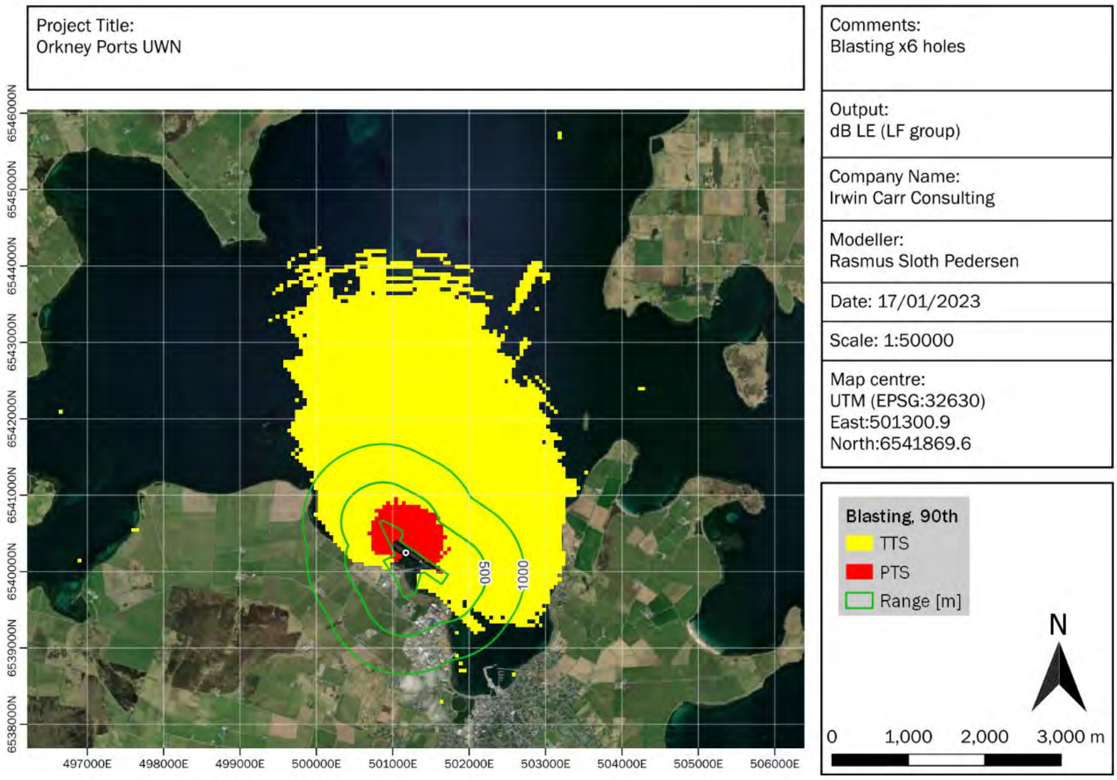
Modeller:
Rasmus Sloth Pedersen

Date: 17/01/2023

Scale: 1:50000

Map centre:
UTM (EPSG:32630)
East:501300.9
North:6541869.6

Figure 35. Blasting, LE, x6, LF group


Project Title:
Orkney Ports UWN

Comments:
Blasting x6 holes

Output:
dB LE (LF group)

Company Name:
Irwin Carr Consulting

Modeller:
Rasmus Sloth Pedersen

Date: 17/01/2023

Scale: 1:50000

Map centre:
UTM (EPSG:32630)
East:501300.9
North:6541869.6

Figure 36. Blasting, L_E, x1, HF group

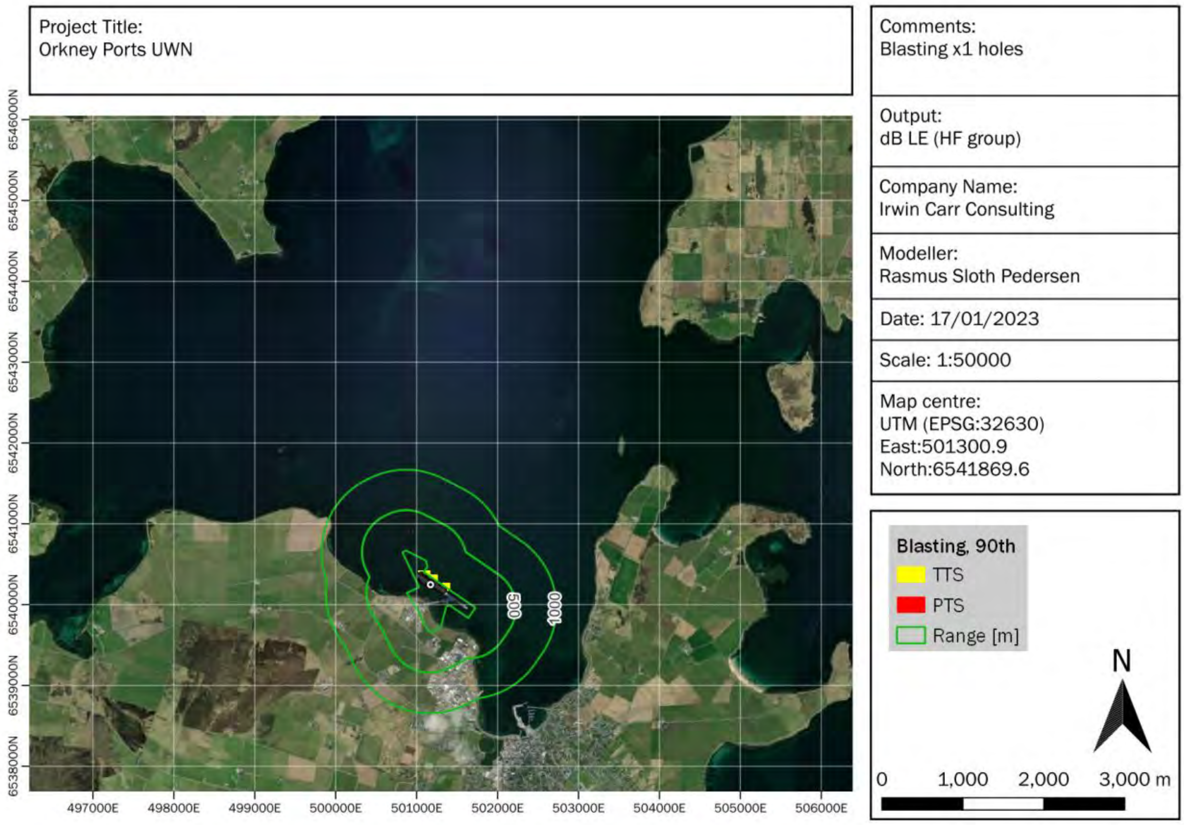


Figure 37. Blasting, L_E, x6, HF group

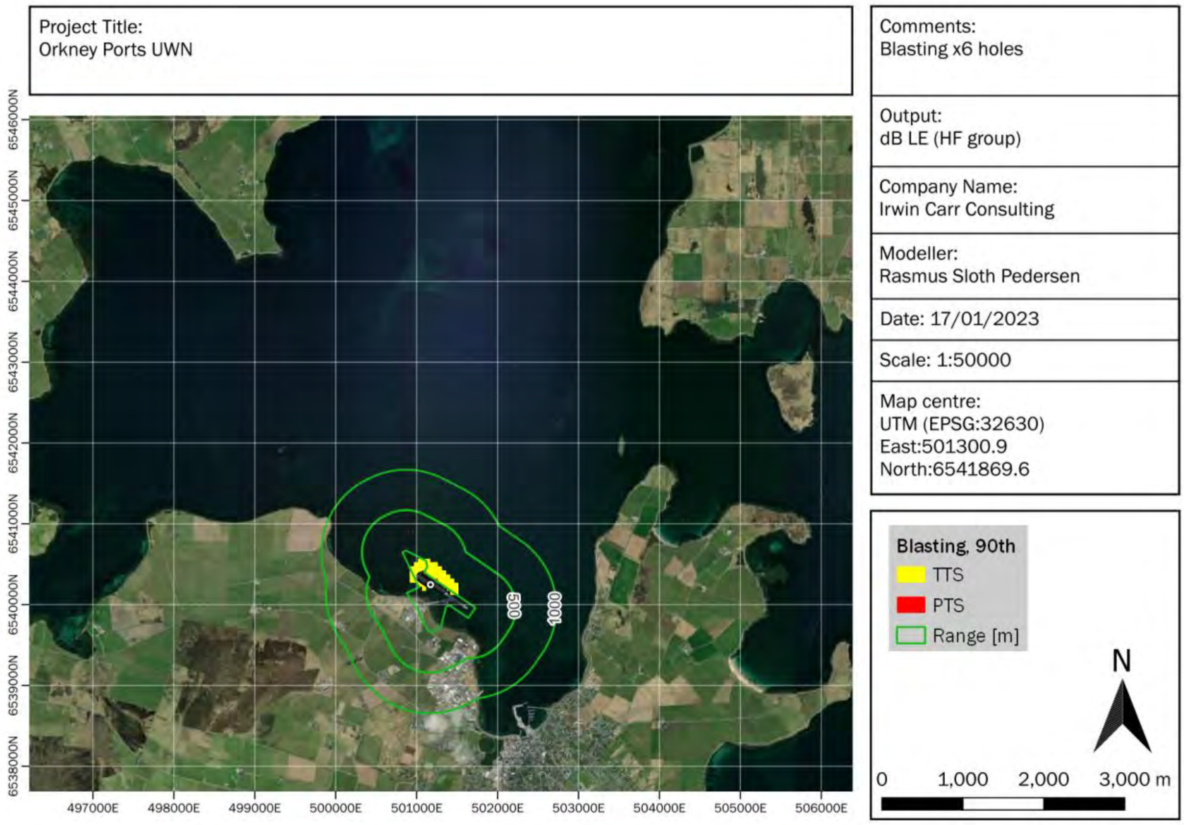
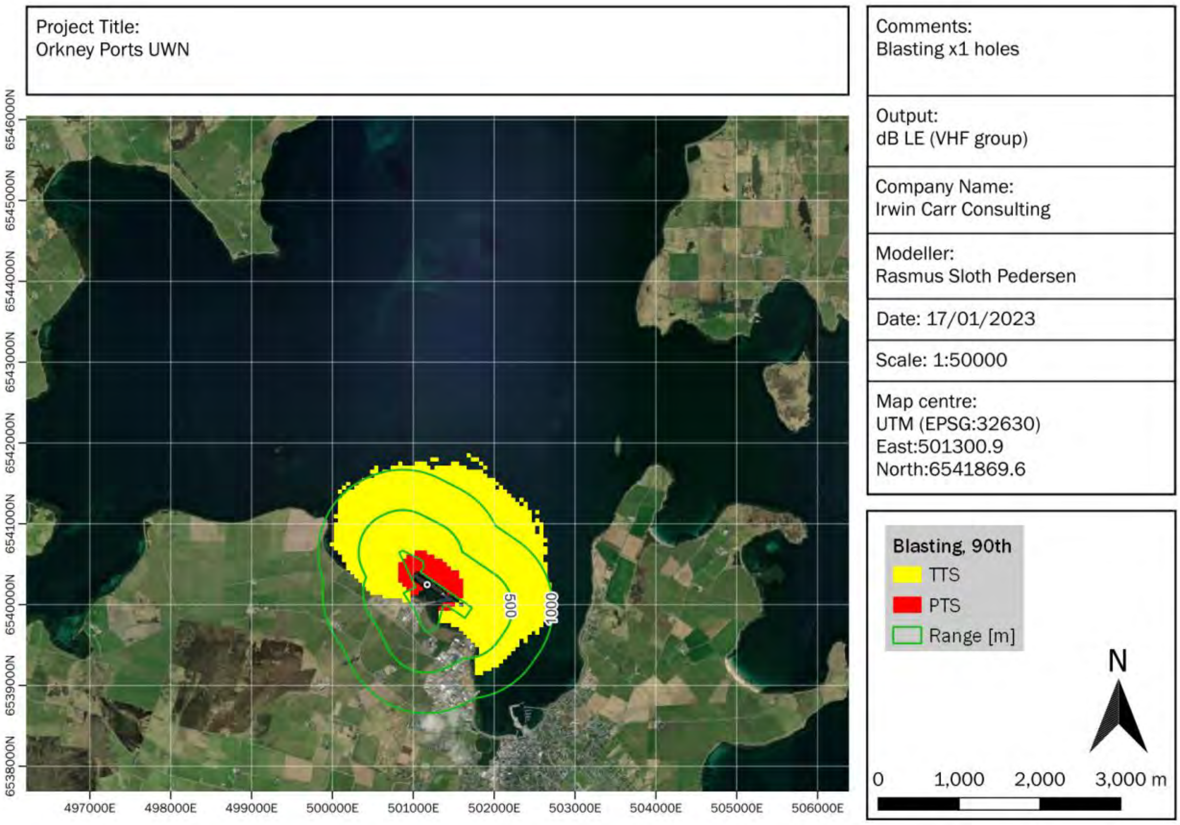


Figure 38. Blasting, L_E, x1, VHF group



Project Title:
Orkney Ports UWN

Comments:
Blasting x1 holes

Output:
dB LE (VHF group)

Company Name:
Irwin Carr Consulting

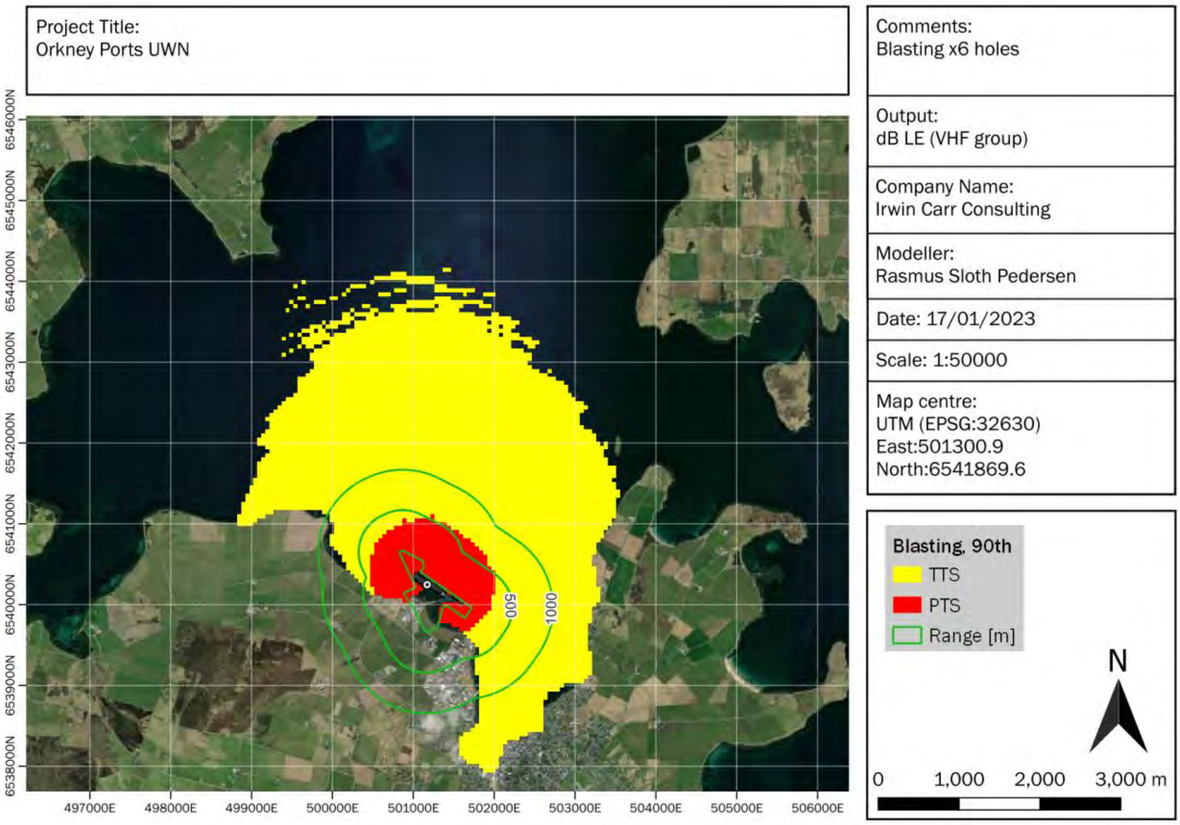
Modeller:
Rasmus Sloth Pedersen

Date: 17/01/2023

Scale: 1:50000

Map centre:
UTM (EPSG:32630)
East:501300.9
North:6541869.6

Figure 39. Blasting, L_E, x6, VHF group



Project Title:
Orkney Ports UWN

Comments:
Blasting x6 holes

Output:
dB LE (VHF group)

Company Name:
Irwin Carr Consulting

Modeller:
Rasmus Sloth Pedersen

Date: 17/01/2023

Scale: 1:50000

Map centre:
UTM (EPSG:32630)
East:501300.9
North:6541869.6

Figure 40. Blasting, L_E, x1, PW group

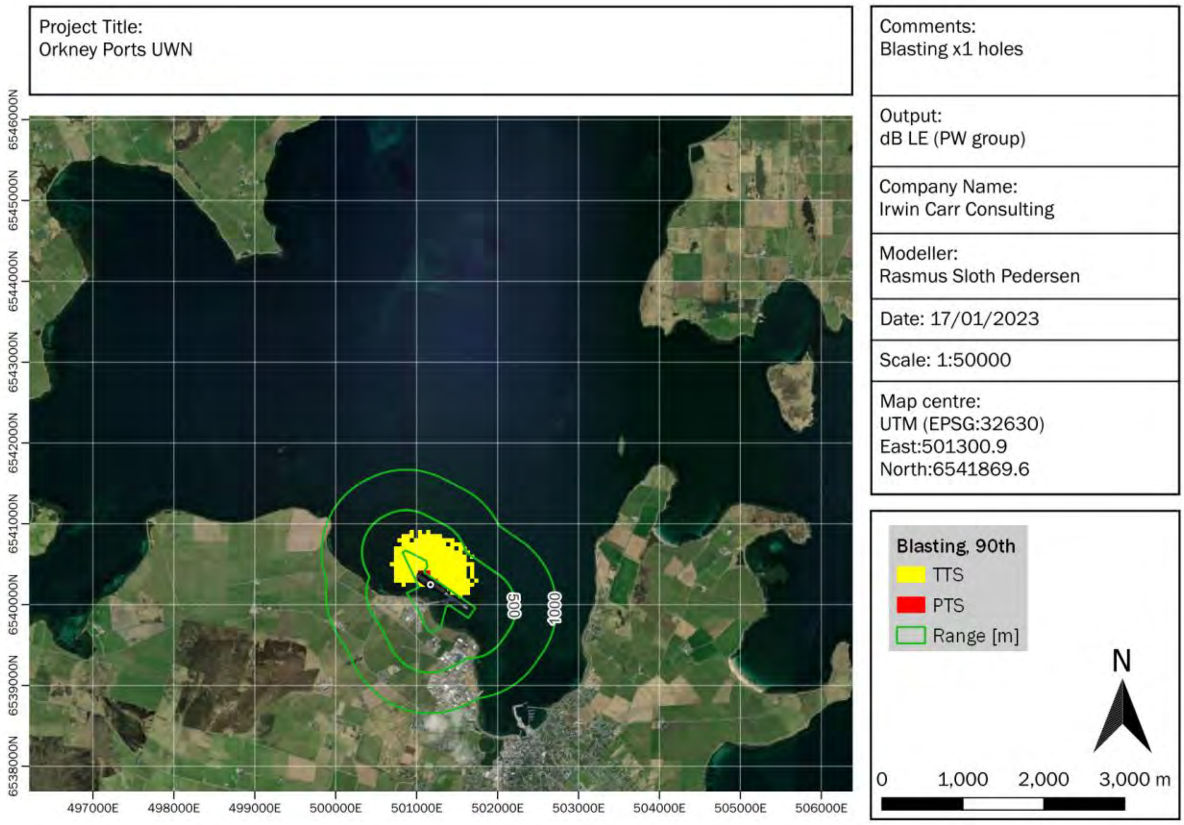


Figure 41. Blasting, L_E, x6, PW group

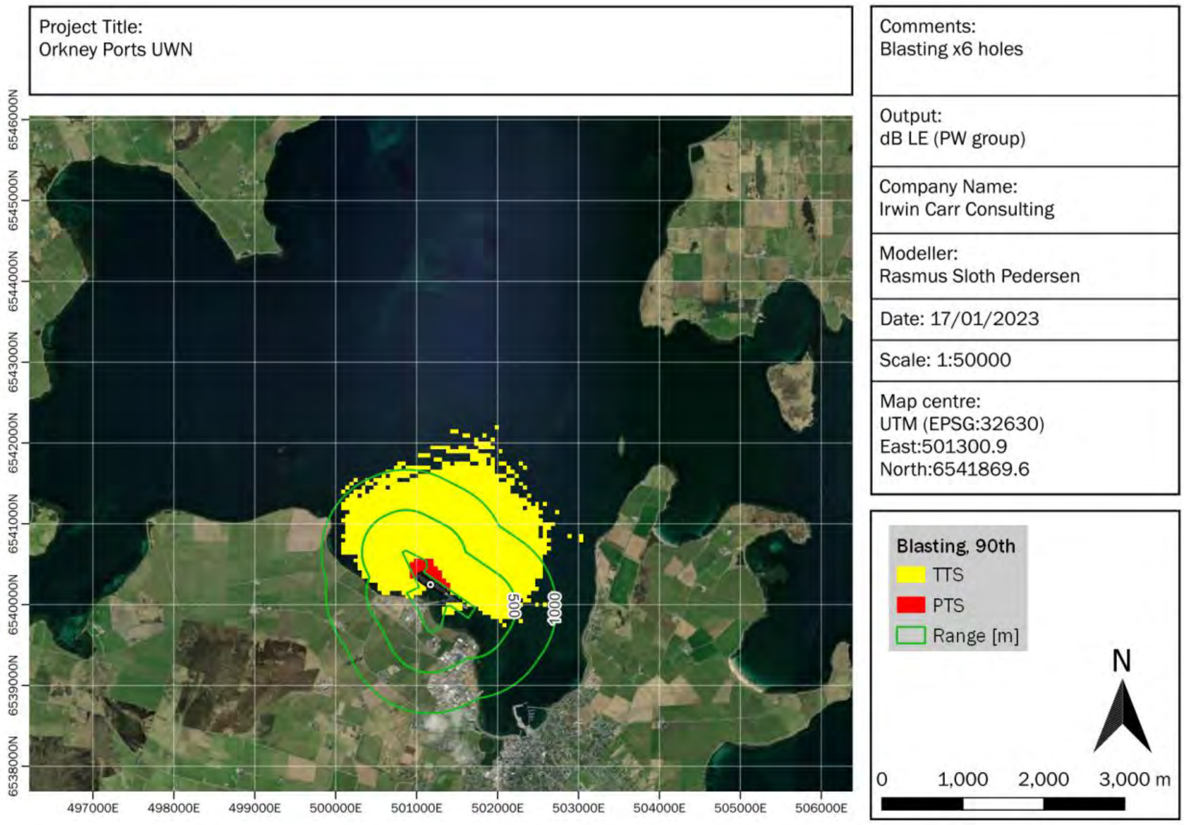


Figure 42. Blasting, L_E, x1, OW group

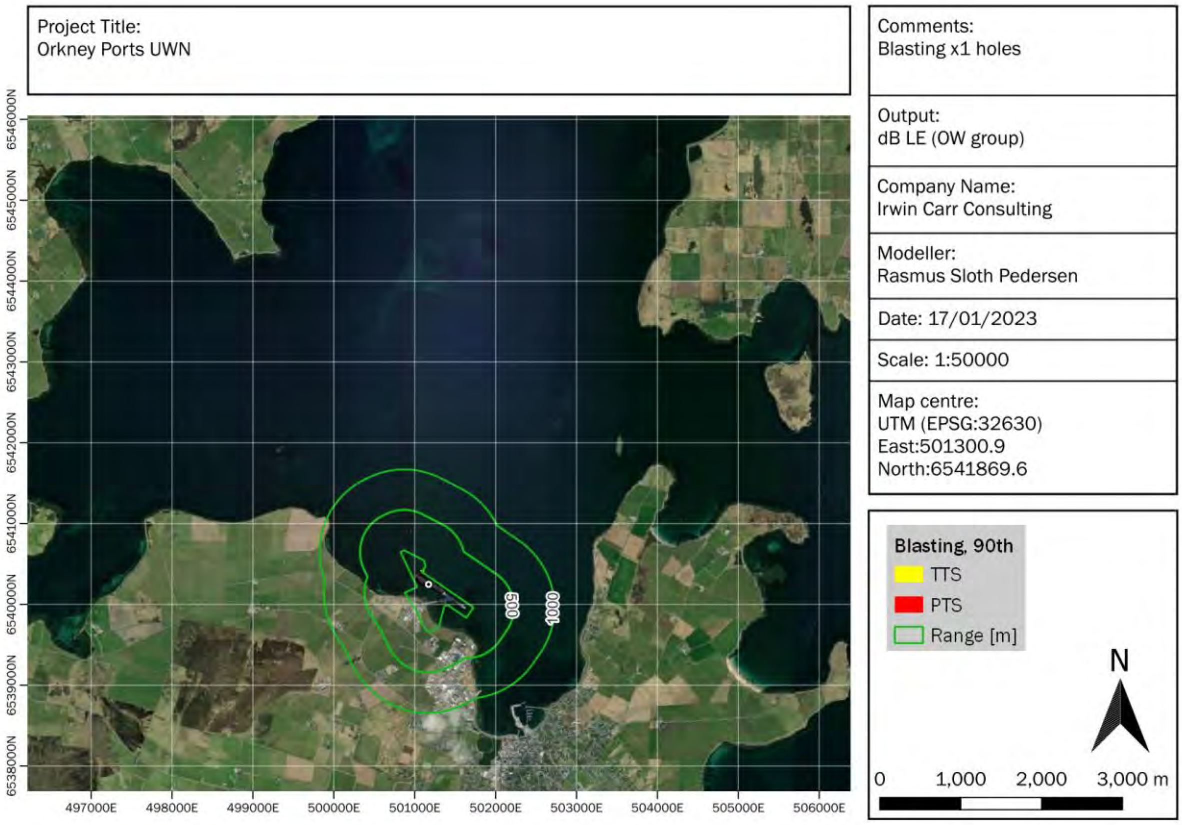


Figure 43. Blasting, L_E, x6, OW group

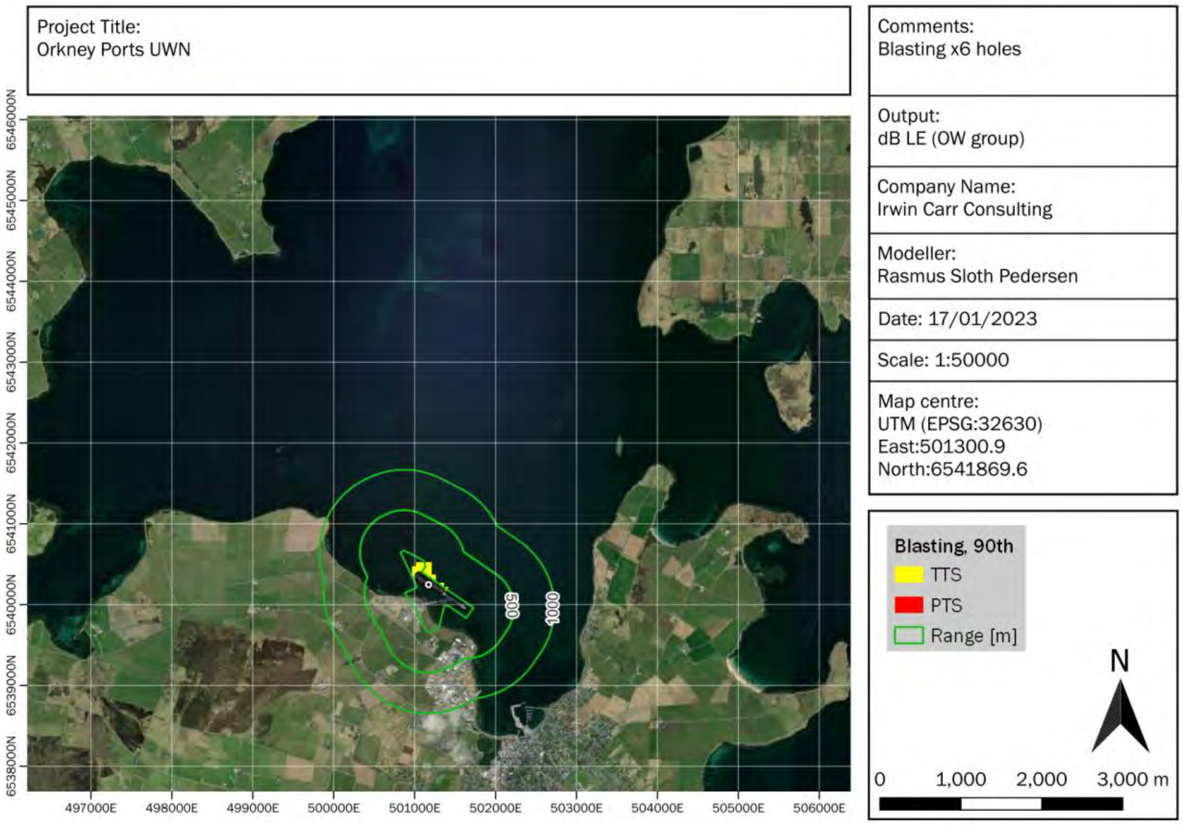
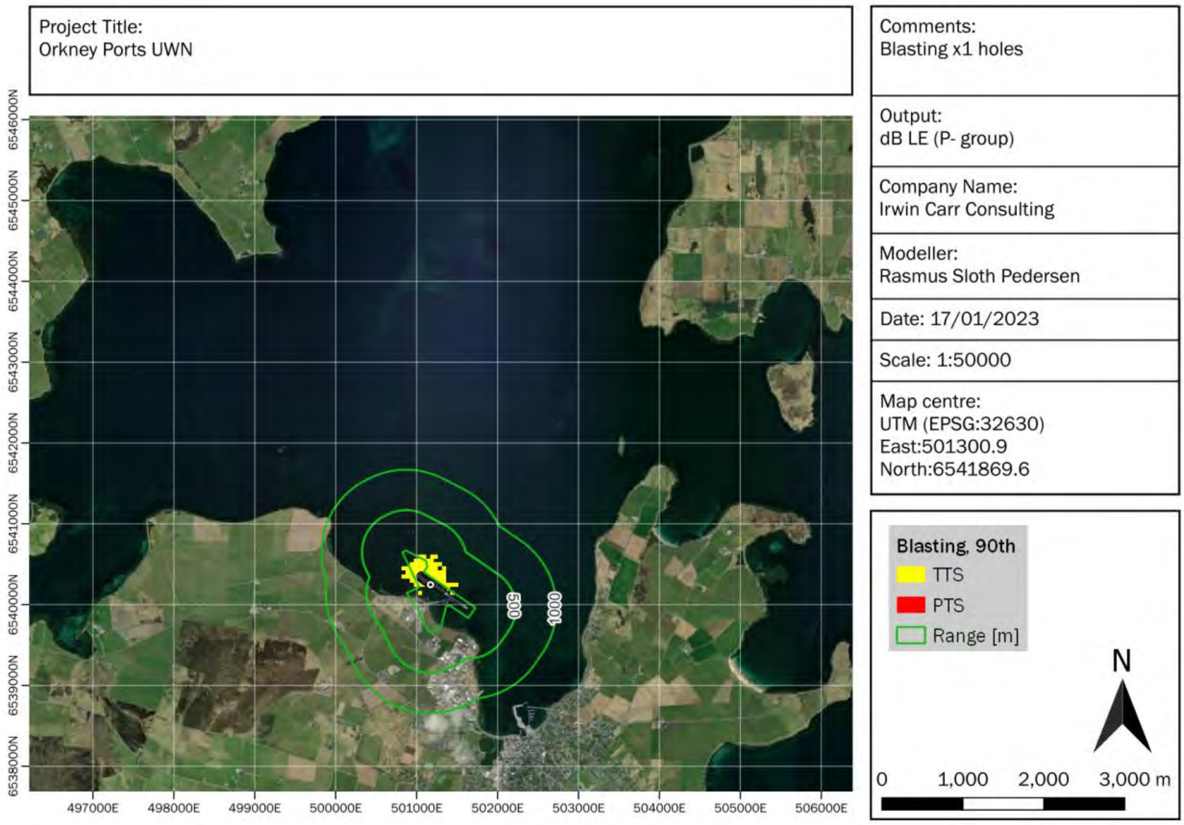


Figure 44. Blasting, L_E, x1, P- group


Project Title:
Orkney Ports UWN

Comments:
Blasting x1 holes

Output:
dB LE (P- group)

Company Name:
Irwin Carr Consulting

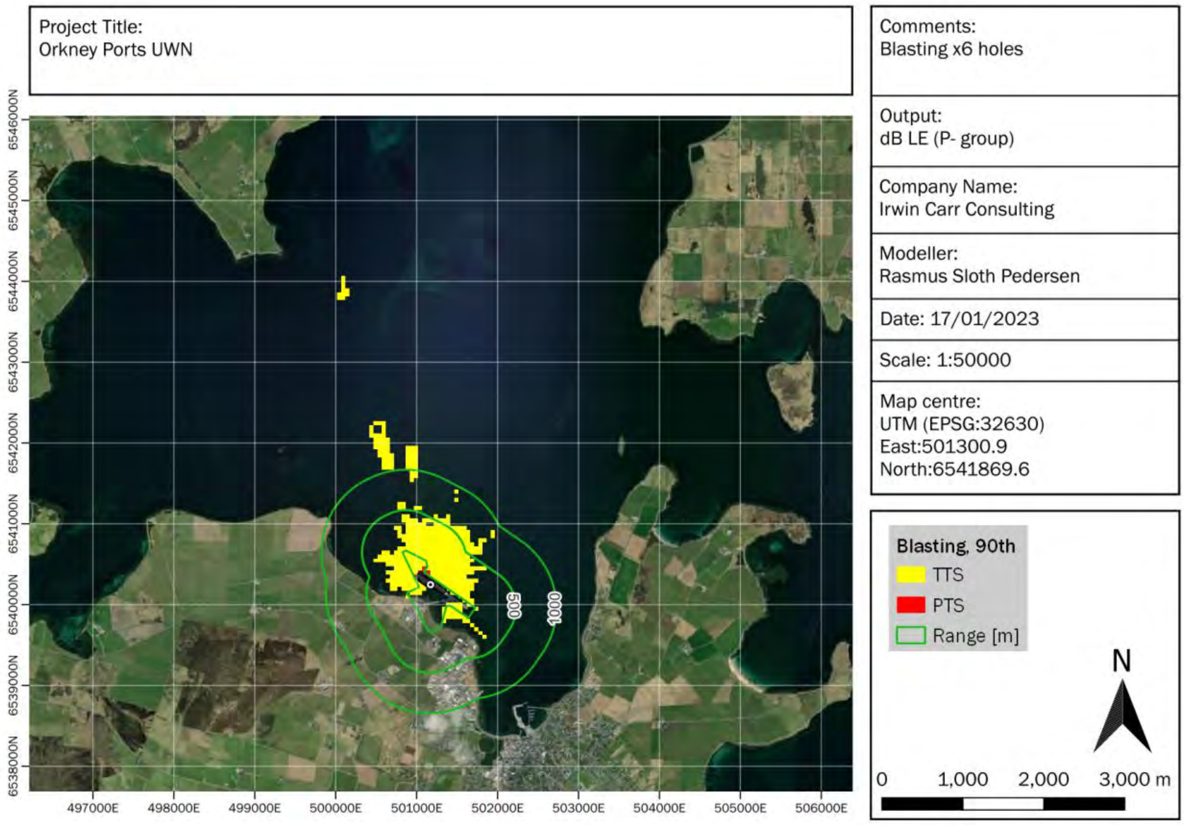
Modeller:
Rasmus Sloth Pedersen

Date: 17/01/2023

Scale: 1:50000

Map centre:
UTM (EPSG:32630)
East:501300.9
North:6541869.6

Figure 45. Blasting, L_E, x6, P- group


Project Title:
Orkney Ports UWN

Comments:
Blasting x6 holes

Output:
dB LE (P- group)

Company Name:
Irwin Carr Consulting

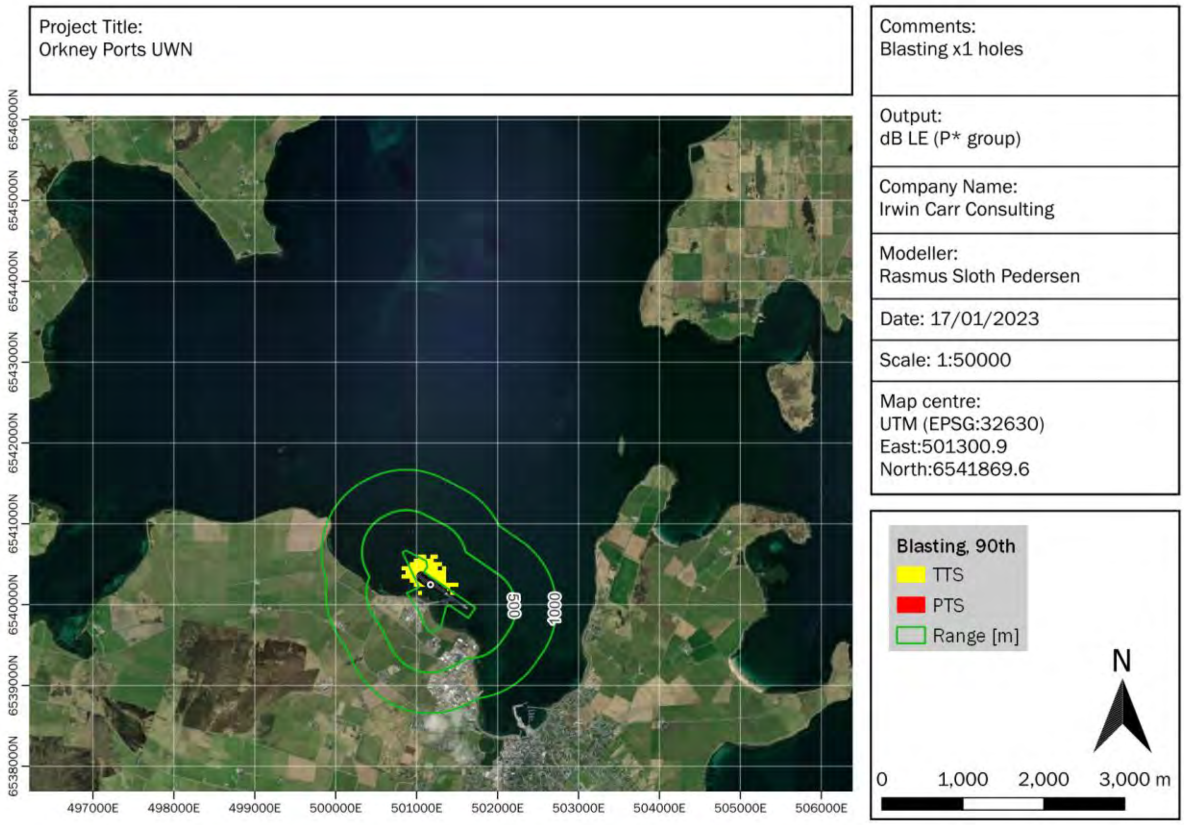
Modeller:
Rasmus Sloth Pedersen

Date: 17/01/2023

Scale: 1:50000

Map centre:
UTM (EPSG:32630)
East:501300.9
North:6541869.6

Figure 46. Blasting, L_E, x1, P* group



Project Title:
Orkney Ports UWN

Comments:
Blasting x1 holes

Output:
dB LE (P* group)

Company Name:
Irwin Carr Consulting

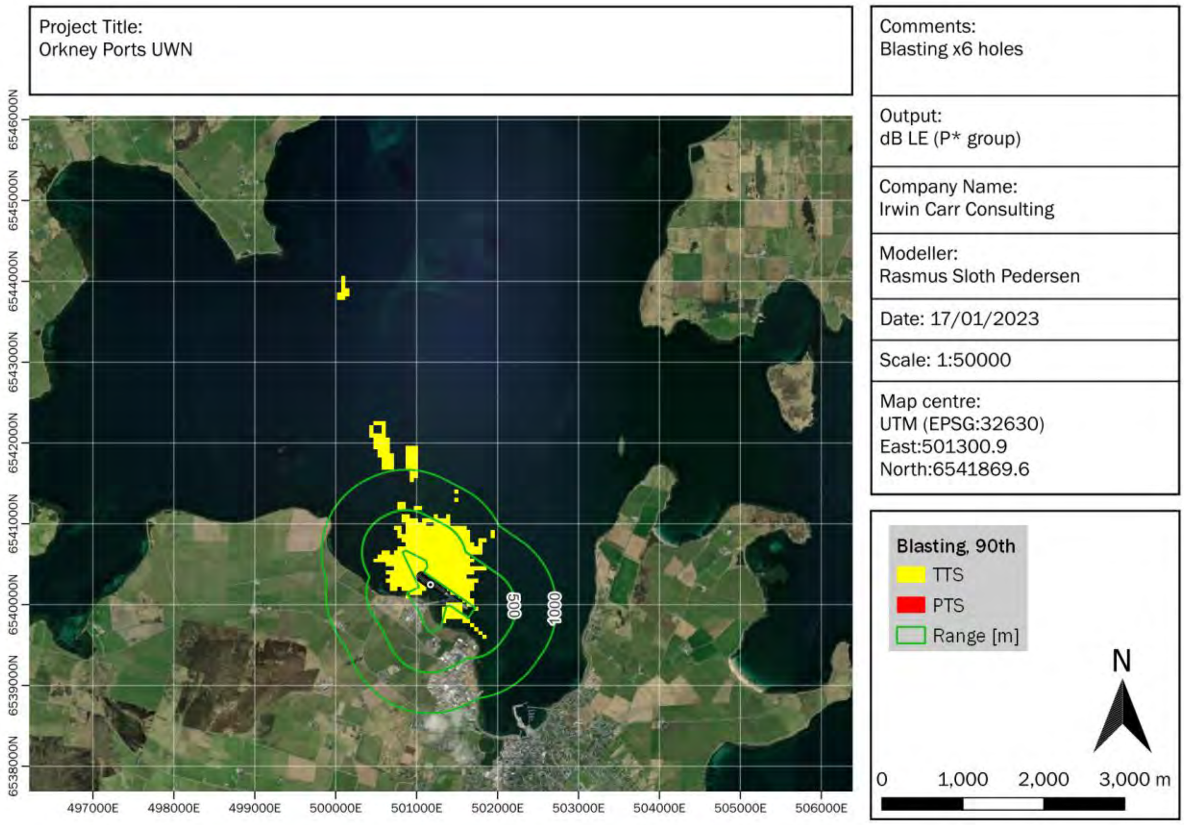
Modeller:
Rasmus Sloth Pedersen

Date: 17/01/2023

Scale: 1:50000

Map centre:
UTM (EPSG:32630)
East:501300.9
North:6541869.6

Figure 47. Blasting, L_E, x6, P* group



Project Title:
Orkney Ports UWN

Comments:
Blasting x6 holes

Output:
dB LE (P* group)

Company Name:
Irwin Carr Consulting

Modeller:
Rasmus Sloth Pedersen

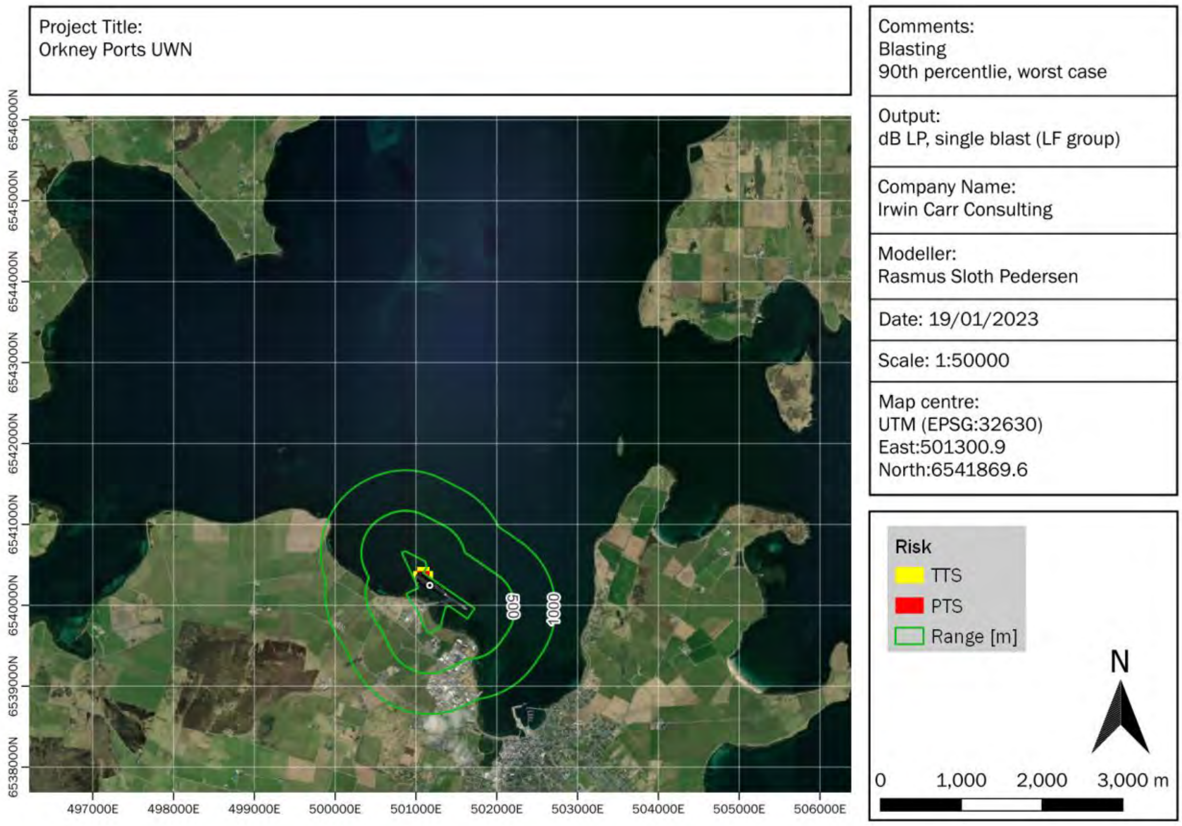
Date: 17/01/2023

Scale: 1:50000

Map centre:
UTM (EPSG:32630)
East:501300.9
North:6541869.6

Blasting L_P

Figure 48. Blasting, L_P, LF group



Project Title:
Orkney Ports UWN

Comments:
Blasting
90th percentile, worst case

Output:
dB LP, single blast (LF group)

Company Name:
Irwin Carr Consulting

Modeller:
Rasmus Sloth Pedersen

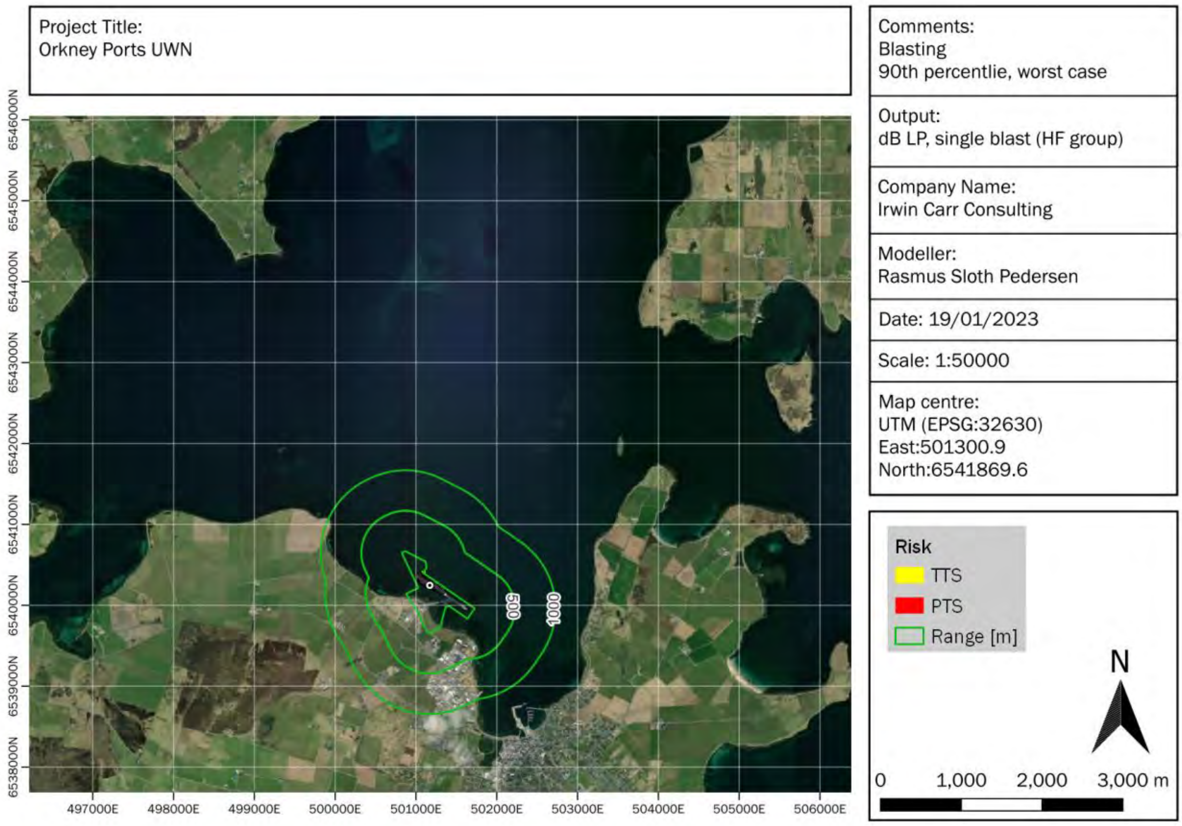
Date: 19/01/2023

Scale: 1:50000

Map centre:
UTM (EPSG:32630)
East:501300.9
North:6541869.6

Risk
🟨 TTS
🟥 PTS
🟩 Range [m]

Figure 49. Blasting, L_P, HF group



Project Title:
Orkney Ports UWN

Comments:
Blasting
90th percentile, worst case

Output:
dB LP, single blast (HF group)

Company Name:
Irwin Carr Consulting

Modeller:
Rasmus Sloth Pedersen

Date: 19/01/2023

Scale: 1:50000

Map centre:
UTM (EPSG:32630)
East:501300.9
North:6541869.6

Risk
🟨 TTS
🟥 PTS
🟩 Range [m]

Figure 50. Blasting, LP, VHF group

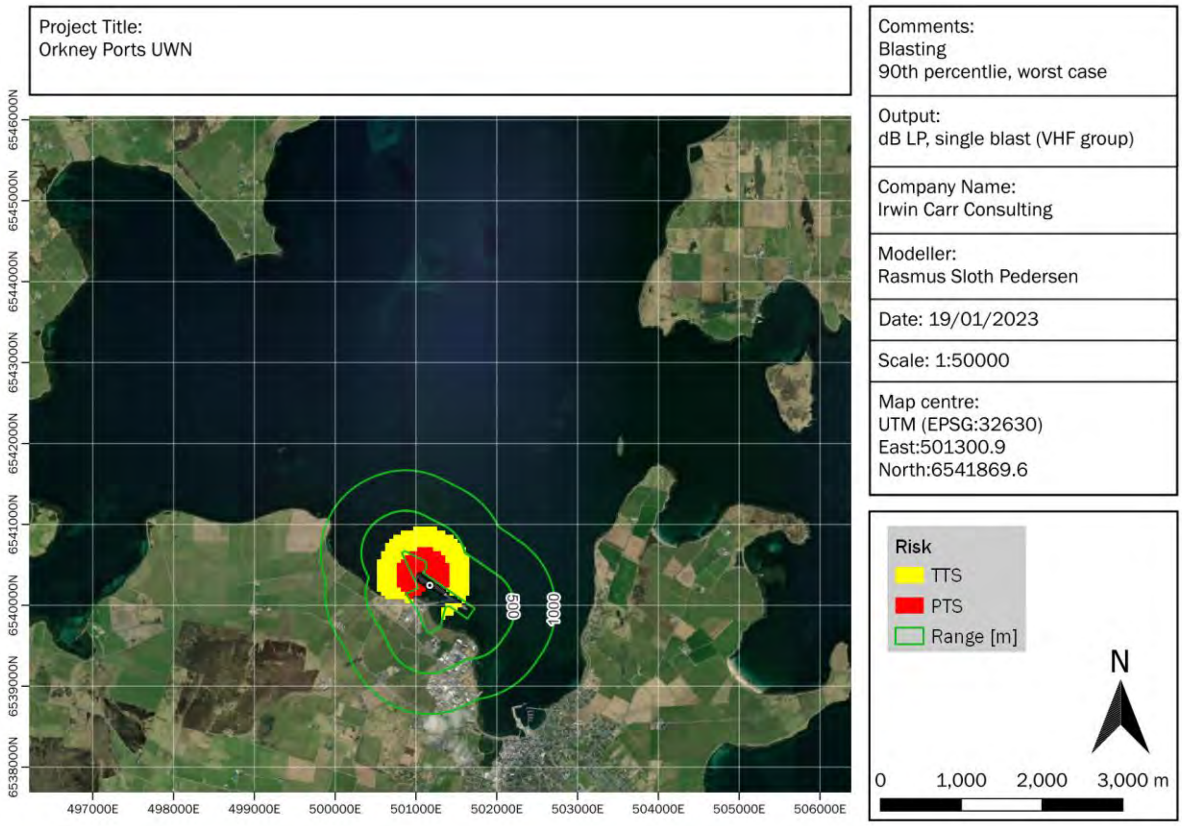


Figure 51. Blasting, LP, PW group

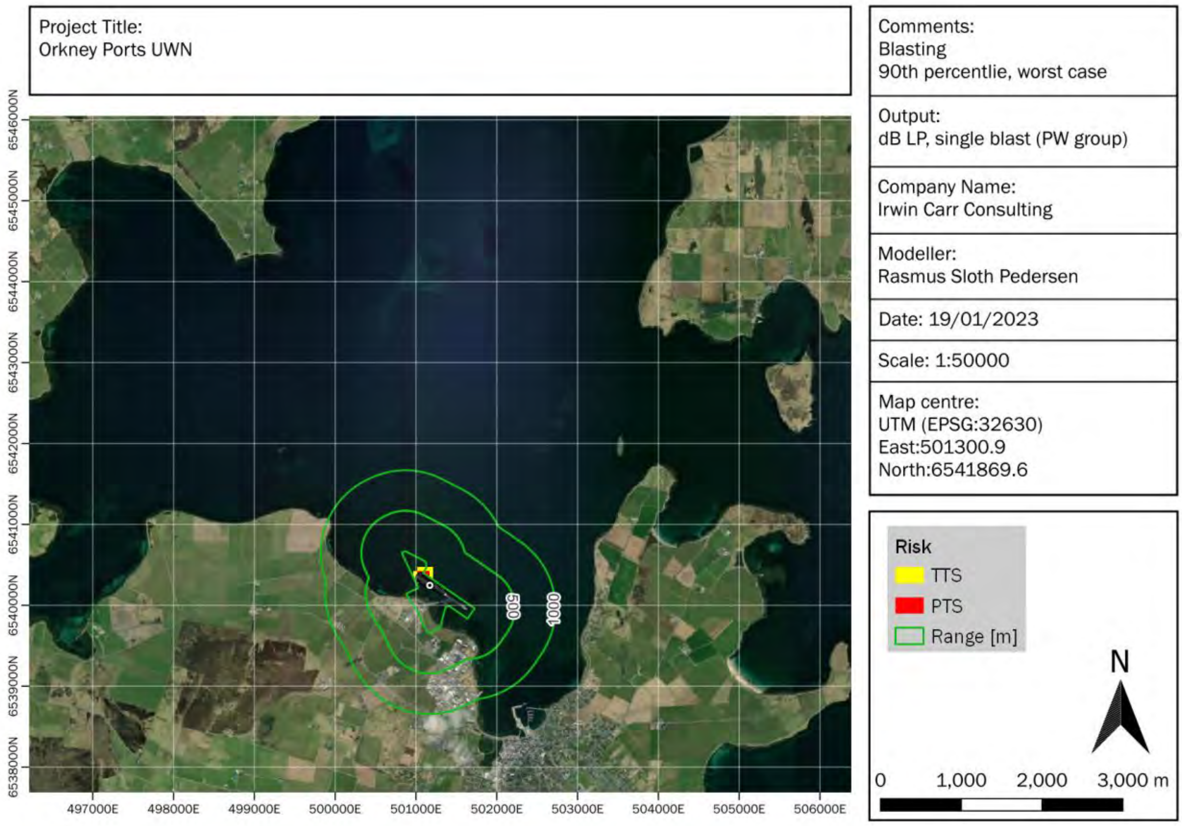
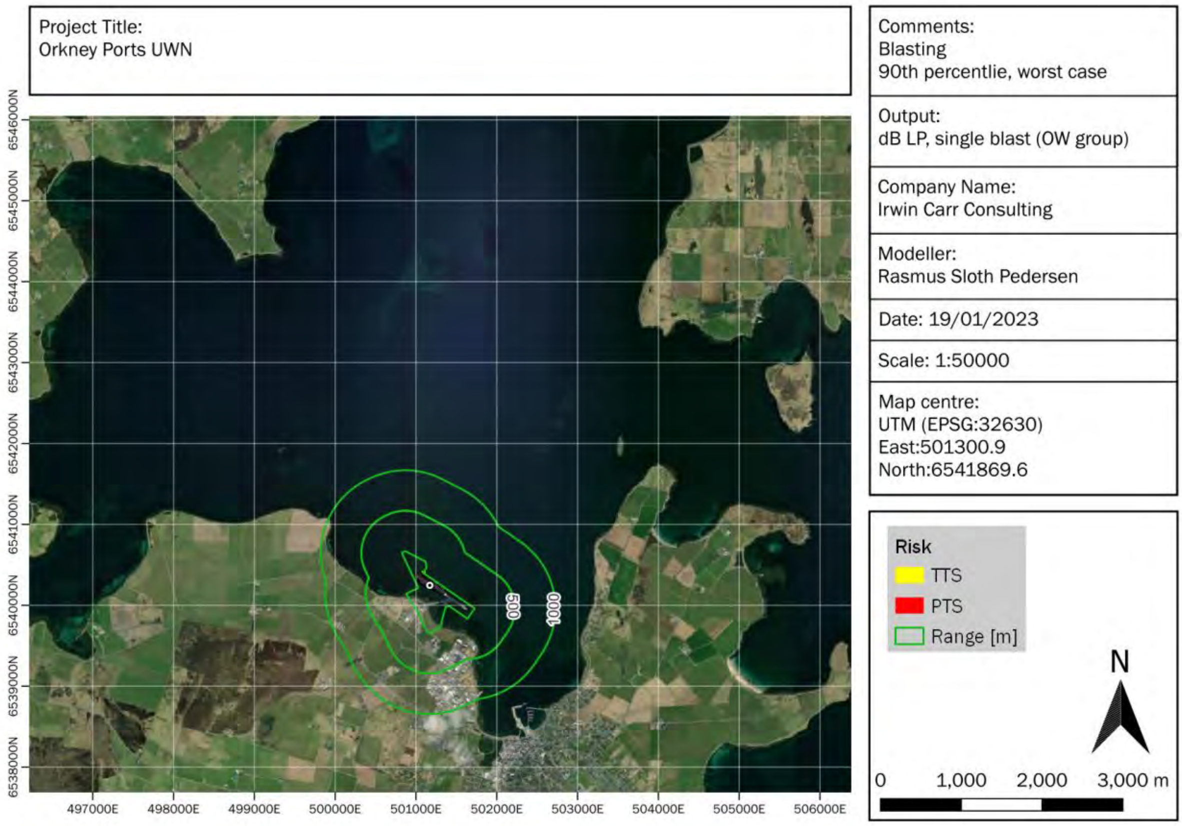


Figure 52. Blasting, LP, OW group



Project Title:
Orkney Ports UWN

Comments:
Blasting
90th percentile, worst case

Output:
dB LP, single blast (OW group)

Company Name:
Irwin Carr Consulting

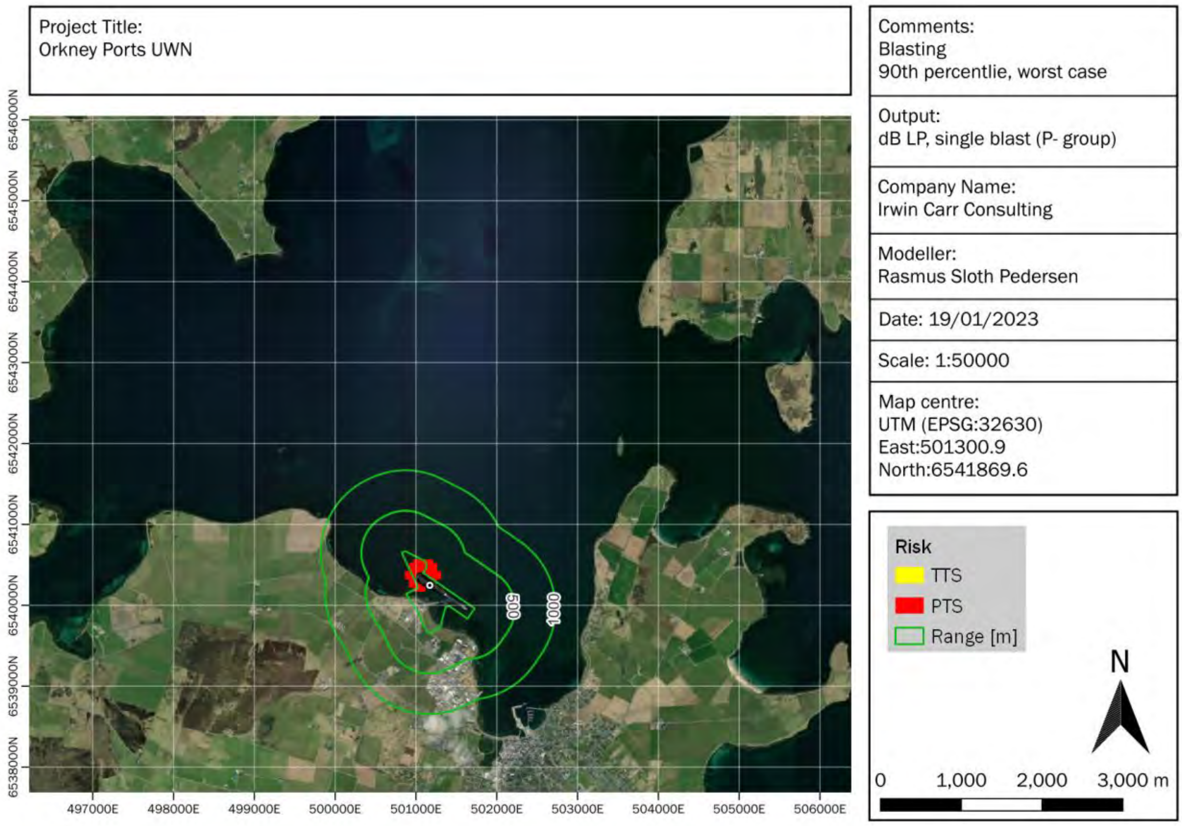
Modeller:
Rasmus Sloth Pedersen

Date: 19/01/2023

Scale: 1:50000

Map centre:
UTM (EPSG:32630)
East:501300.9
North:6541869.6

Figure 53. Blasting, LP, P- group



Project Title:
Orkney Ports UWN

Comments:
Blasting
90th percentile, worst case

Output:
dB LP, single blast (P- group)

Company Name:
Irwin Carr Consulting

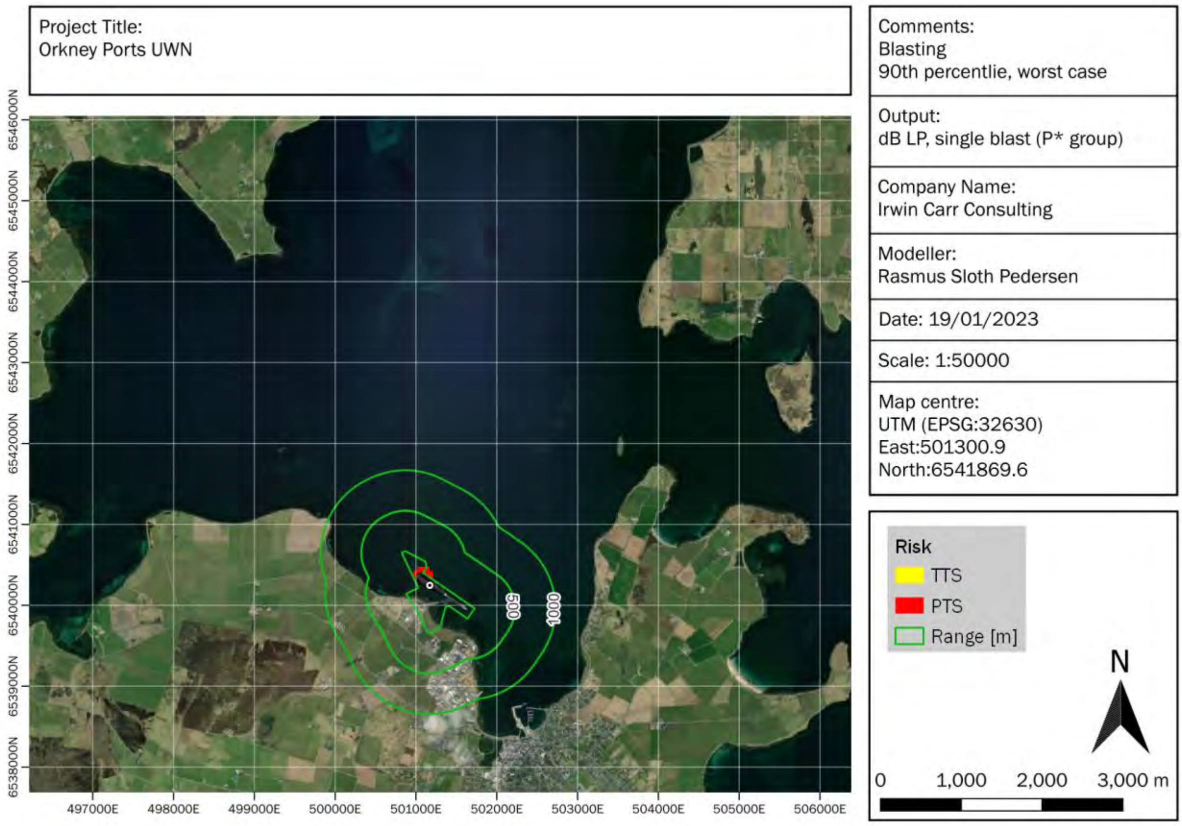
Modeller:
Rasmus Sloth Pedersen

Date: 19/01/2023

Scale: 1:50000

Map centre:
UTM (EPSG:32630)
East:501300.9
North:6541869.6

Figure 54. Blasting, L_P, P* group



Project Title:
Orkney Ports UWN

Comments:
Blasting
90th percentlie, worst case

Output:
dB LP, single blast (P* group)

Company Name:
Irwin Carr Consulting

Modeller:
Rasmus Sloth Pedersen

Date: 19/01/2023

Scale: 1:50000

Map centre:
UTM (EPSG:32630)
East:501300.9
North:6541869.6

Dredging L_E

Maps are provided for 90th percentile source levels for 1 hours and 8 hours.

Figure 55. Dredging, L_E, 1hr, LF group

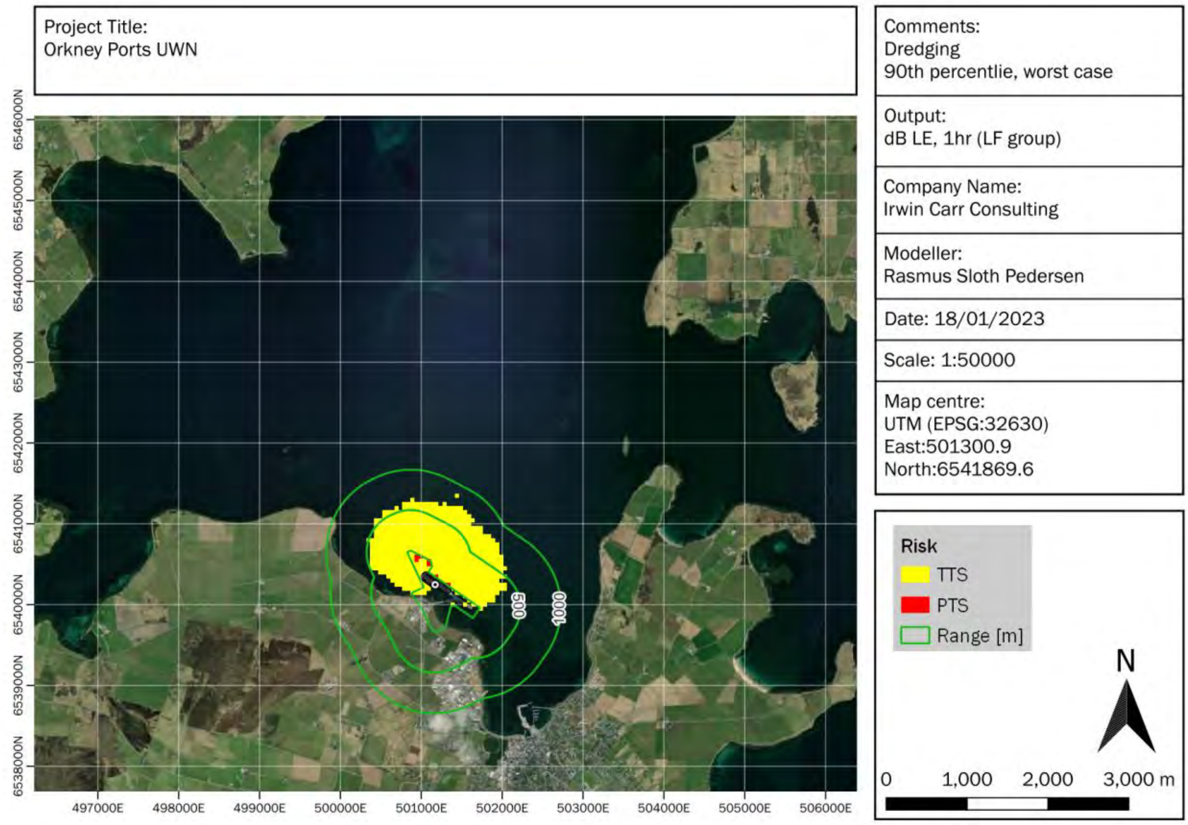
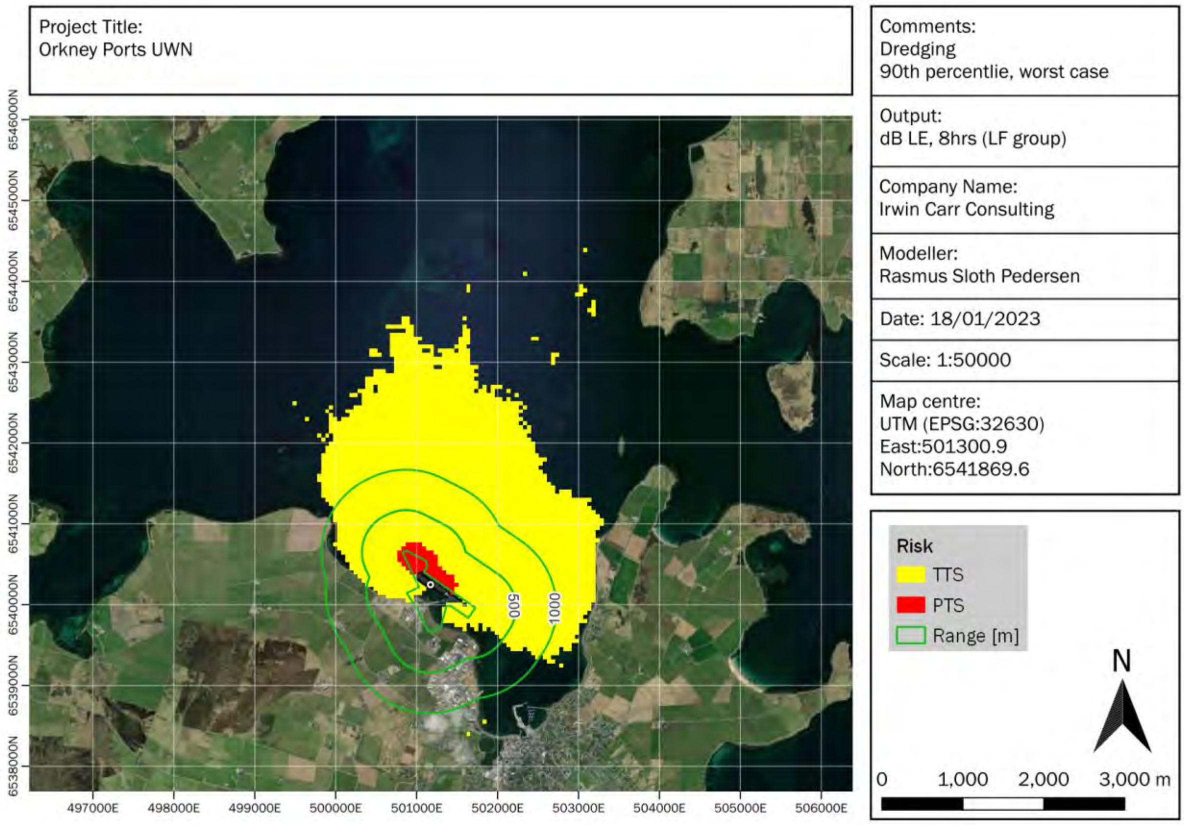


Figure 56. Dredging, L_E, 8hrs, LF group



Project Title:
Orkney Ports UWN

Comments:
Dredging
90th percentile, worst case

Output:
dB LE, 8hrs (LF group)

Company Name:
Irwin Carr Consulting

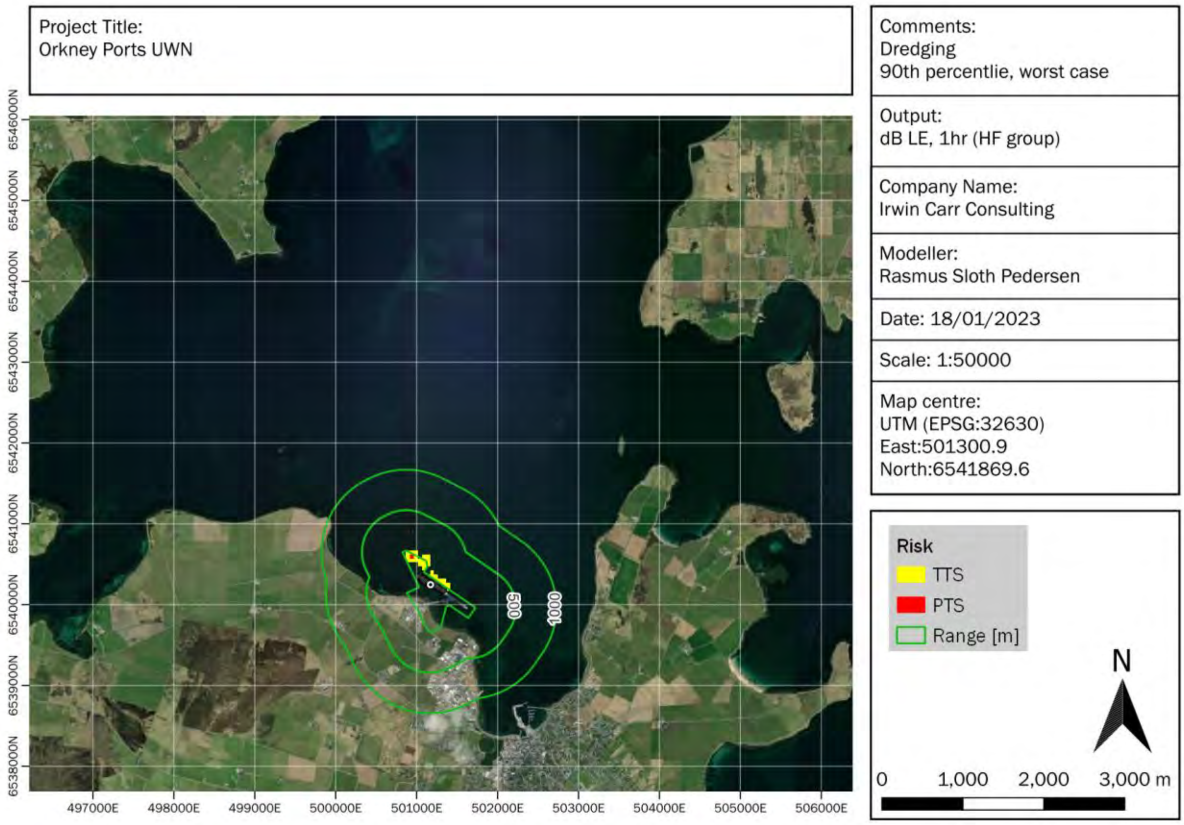
Modeller:
Rasmus Sloth Pedersen

Date: 18/01/2023

Scale: 1:50000

Map centre:
UTM (EPSG:32630)
East:501300.9
North:6541869.6

Figure 57. Dredging, L_E, 1hr, HF group



Project Title:
Orkney Ports UWN

Comments:
Dredging
90th percentile, worst case

Output:
dB LE, 1hr (HF group)

Company Name:
Irwin Carr Consulting

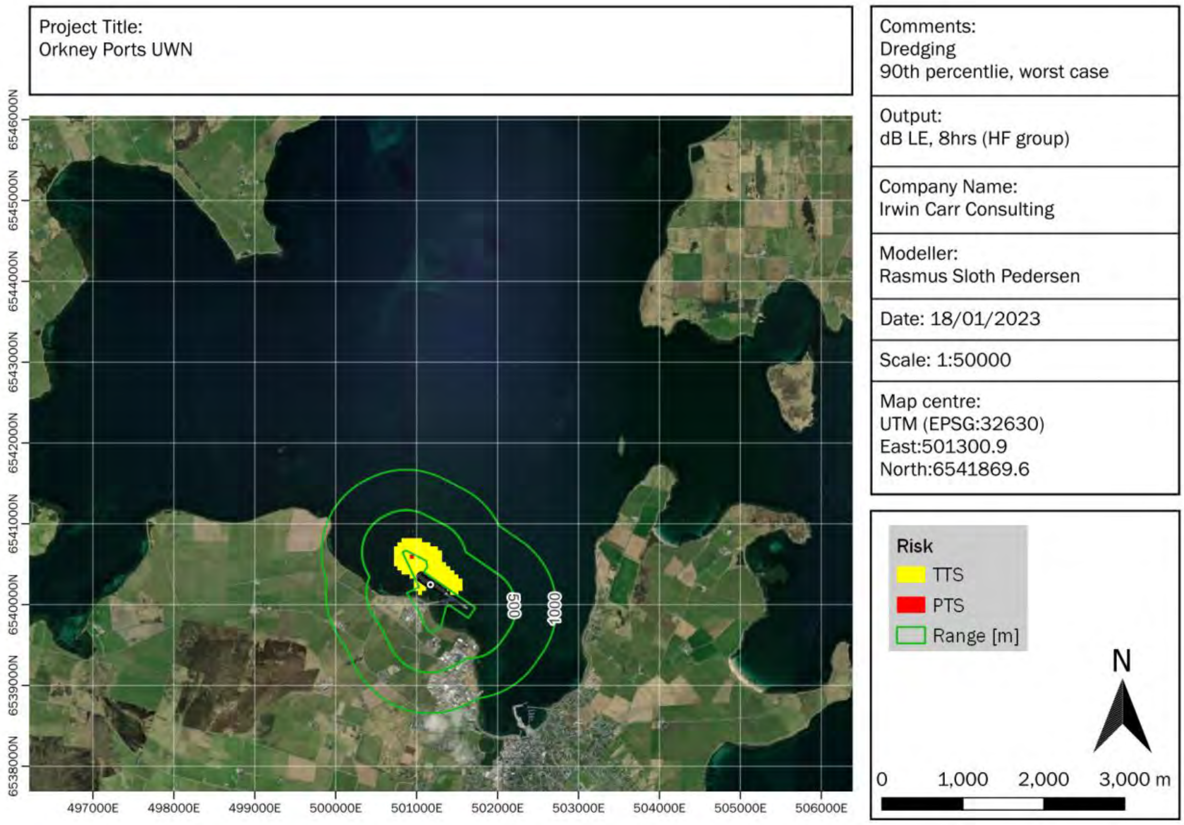
Modeller:
Rasmus Sloth Pedersen

Date: 18/01/2023

Scale: 1:50000

Map centre:
UTM (EPSG:32630)
East:501300.9
North:6541869.6

Figure 58. Dredging, L_E, 8hrs, HF group



Project Title:
Orkney Ports UWN

Comments:
Dredging
90th percentile, worst case

Output:
dB LE, 8hrs (HF group)

Company Name:
Irwin Carr Consulting

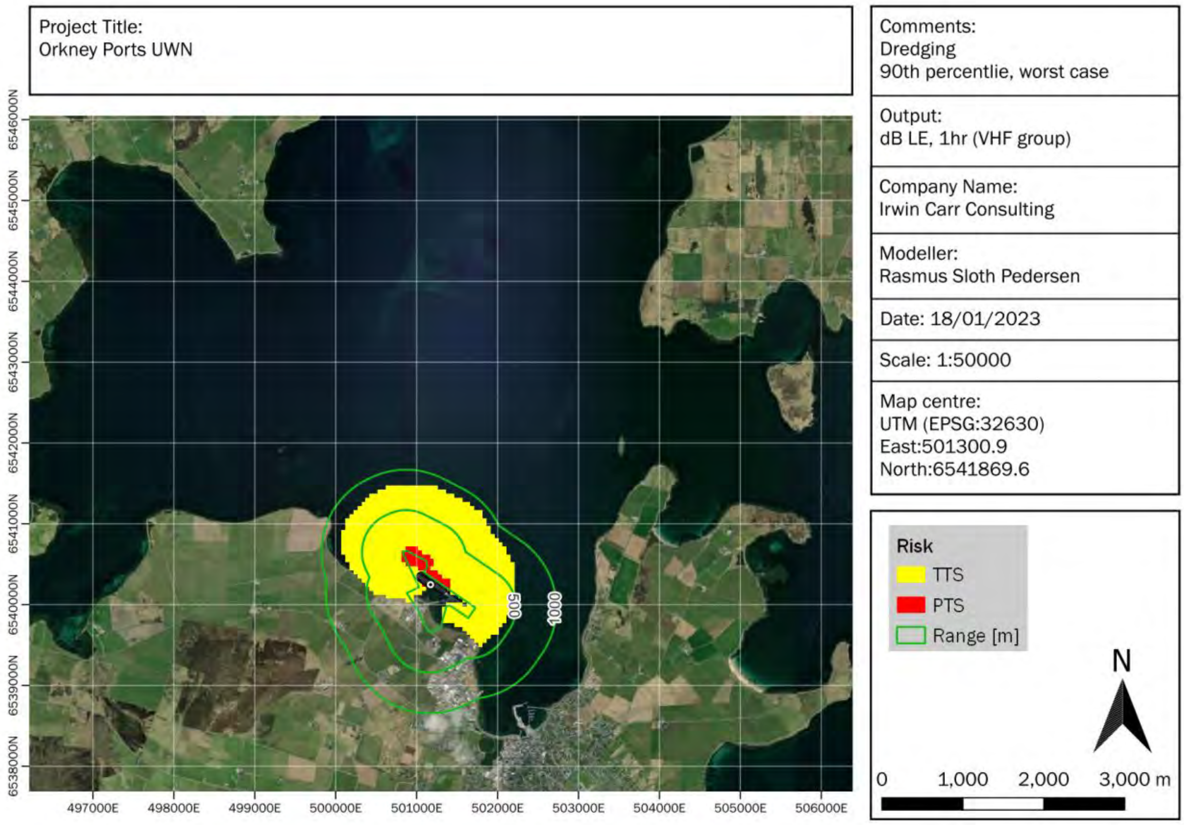
Modeller:
Rasmus Sloth Pedersen

Date: 18/01/2023

Scale: 1:50000

Map centre:
UTM (EPSG:32630)
East:501300.9
North:6541869.6

Figure 59. Dredging, L_E, 1hr, VHF group



Project Title:
Orkney Ports UWN

Comments:
Dredging
90th percentile, worst case

Output:
dB LE, 1hr (VHF group)

Company Name:
Irwin Carr Consulting

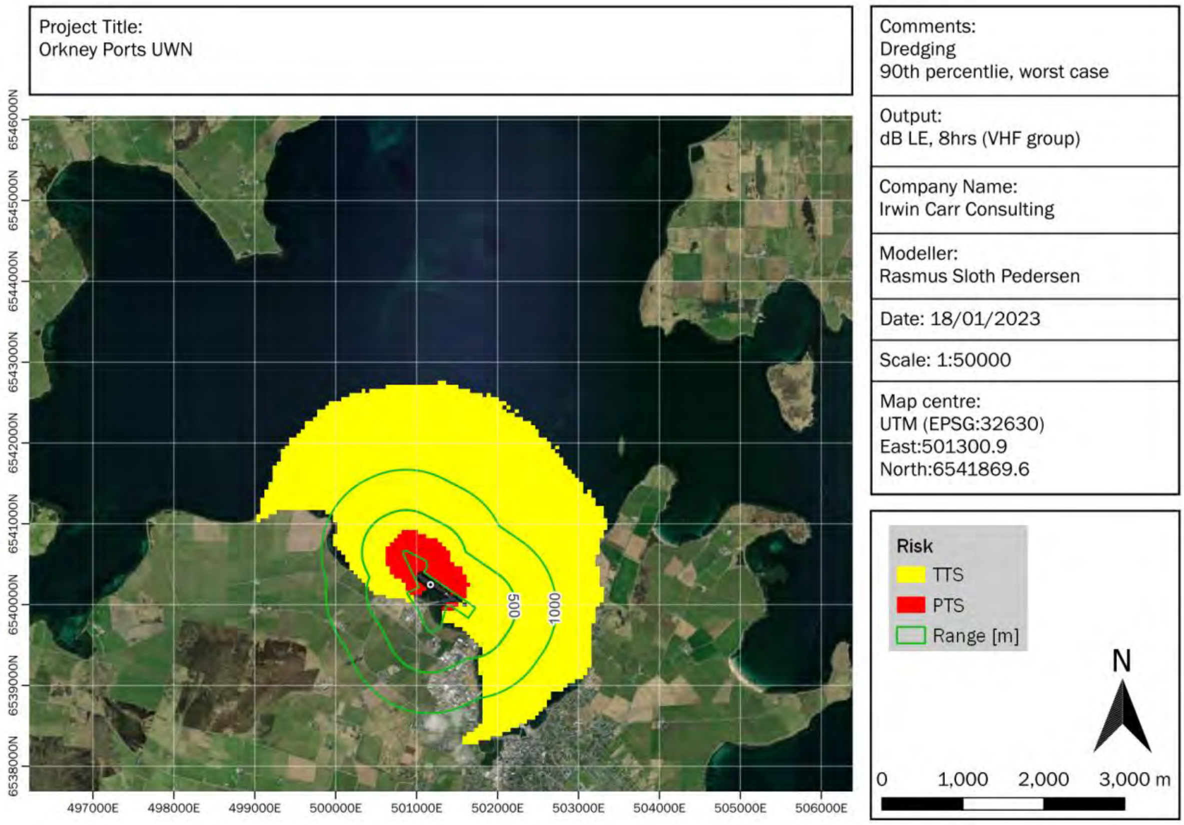
Modeller:
Rasmus Sloth Pedersen

Date: 18/01/2023

Scale: 1:50000

Map centre:
UTM (EPSG:32630)
East:501300.9
North:6541869.6

Figure 60. Dredging, L_E, 8hrs, VHF group



Project Title:
Orkney Ports UWN

Comments:
Dredging
90th percentile, worst case

Output:
dB LE, 8hrs (VHF group)

Company Name:
Irwin Carr Consulting

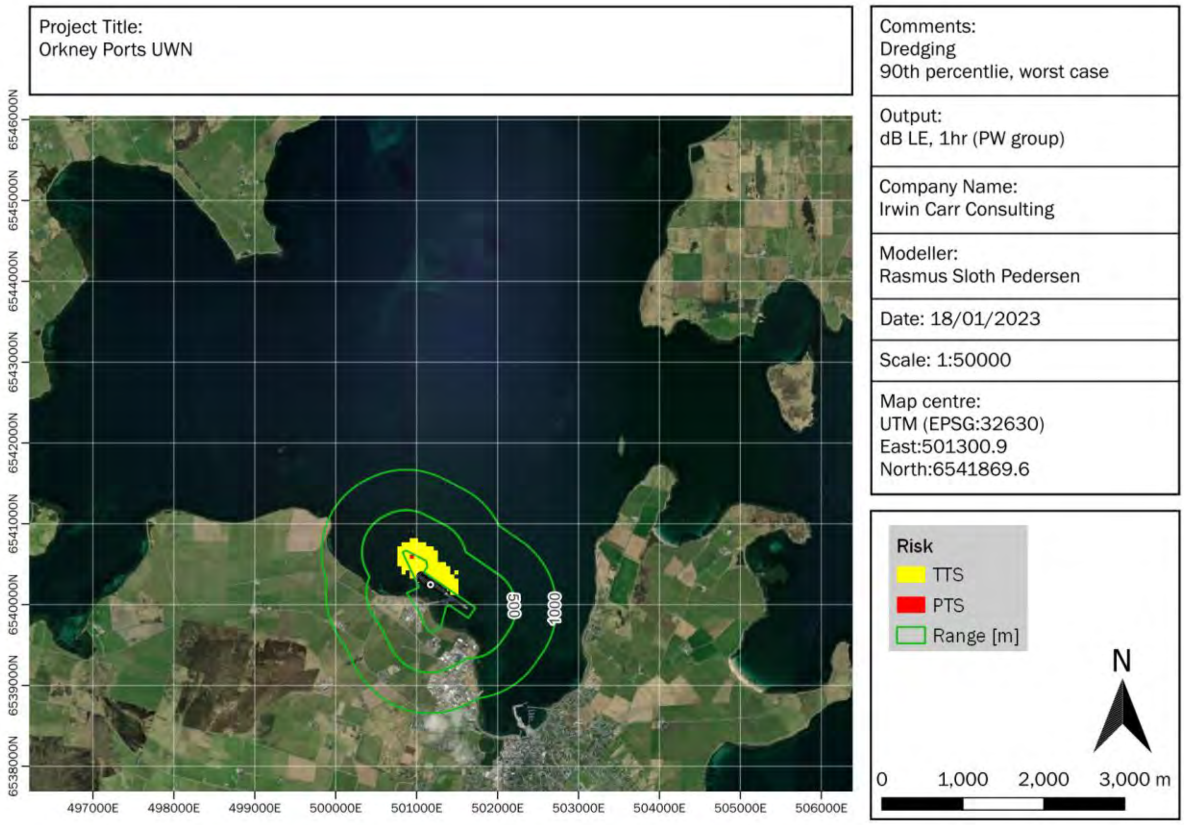
Modeller:
Rasmus Sloth Pedersen

Date: 18/01/2023

Scale: 1:50000

Map centre:
UTM (EPSG:32630)
East:501300.9
North:6541869.6

Figure 61. Dredging, L_E, 1hr, PW group



Project Title:
Orkney Ports UWN

Comments:
Dredging
90th percentile, worst case

Output:
dB LE, 1hr (PW group)

Company Name:
Irwin Carr Consulting

Modeller:
Rasmus Sloth Pedersen

Date: 18/01/2023

Scale: 1:50000

Map centre:
UTM (EPSG:32630)
East:501300.9
North:6541869.6

Figure 62. Dredging, L_E, 8hrs, PW group

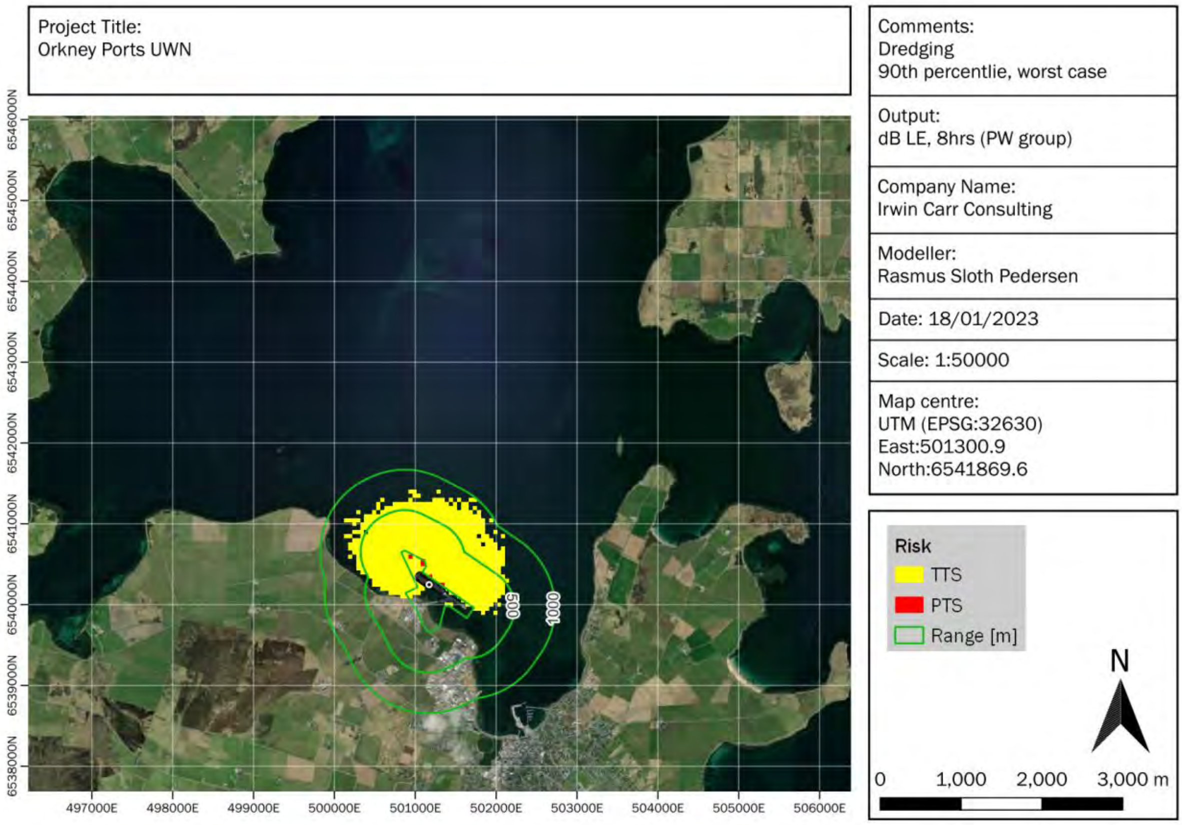


Figure 63. Dredging, L_E, 1hr, OW group

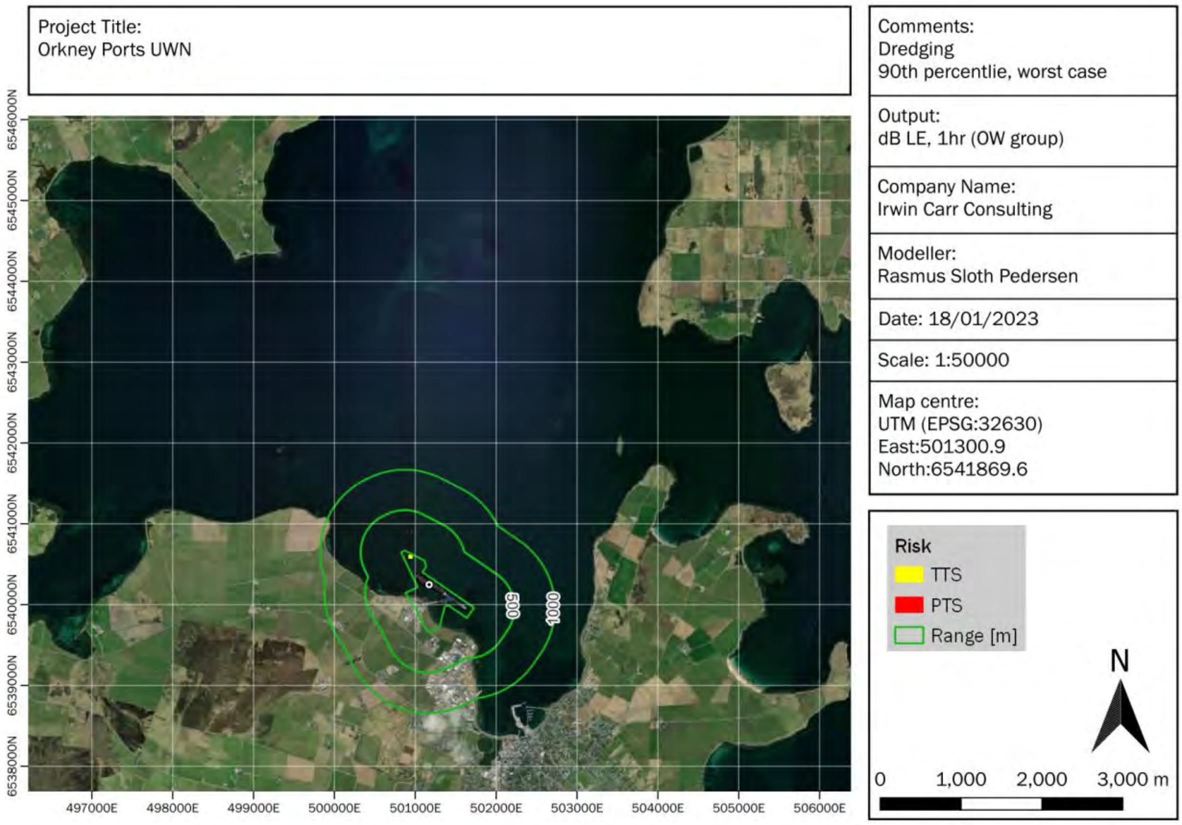


Figure 64. Dredging, L_E, 8hrs, OW group

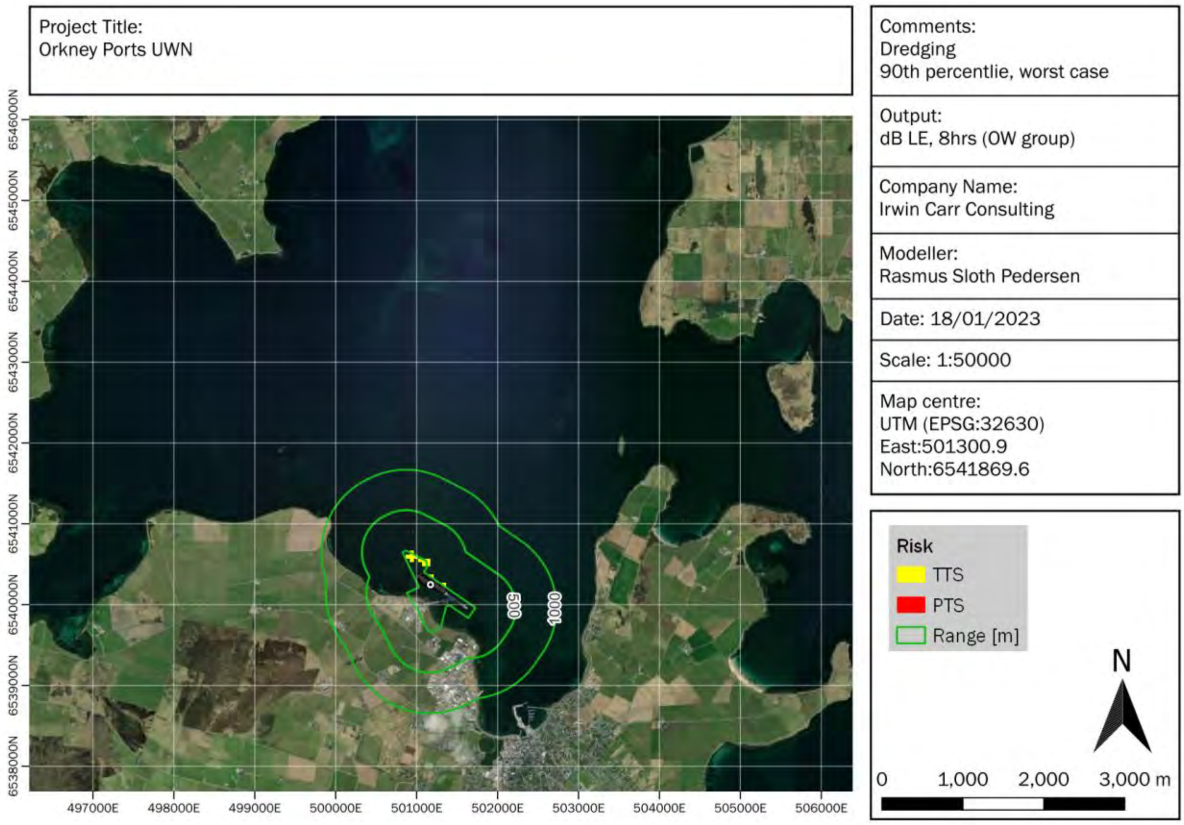


Figure 65. Dredging, L_E, 1hr, P- group

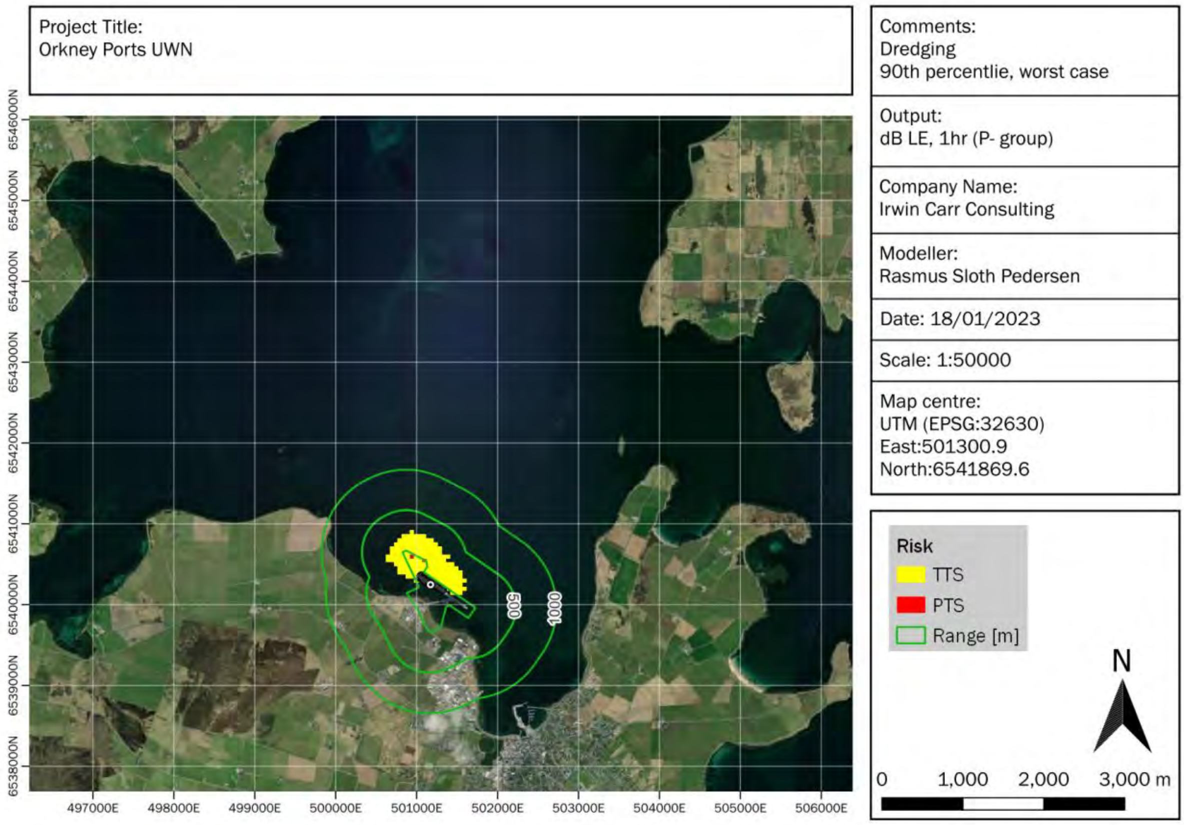
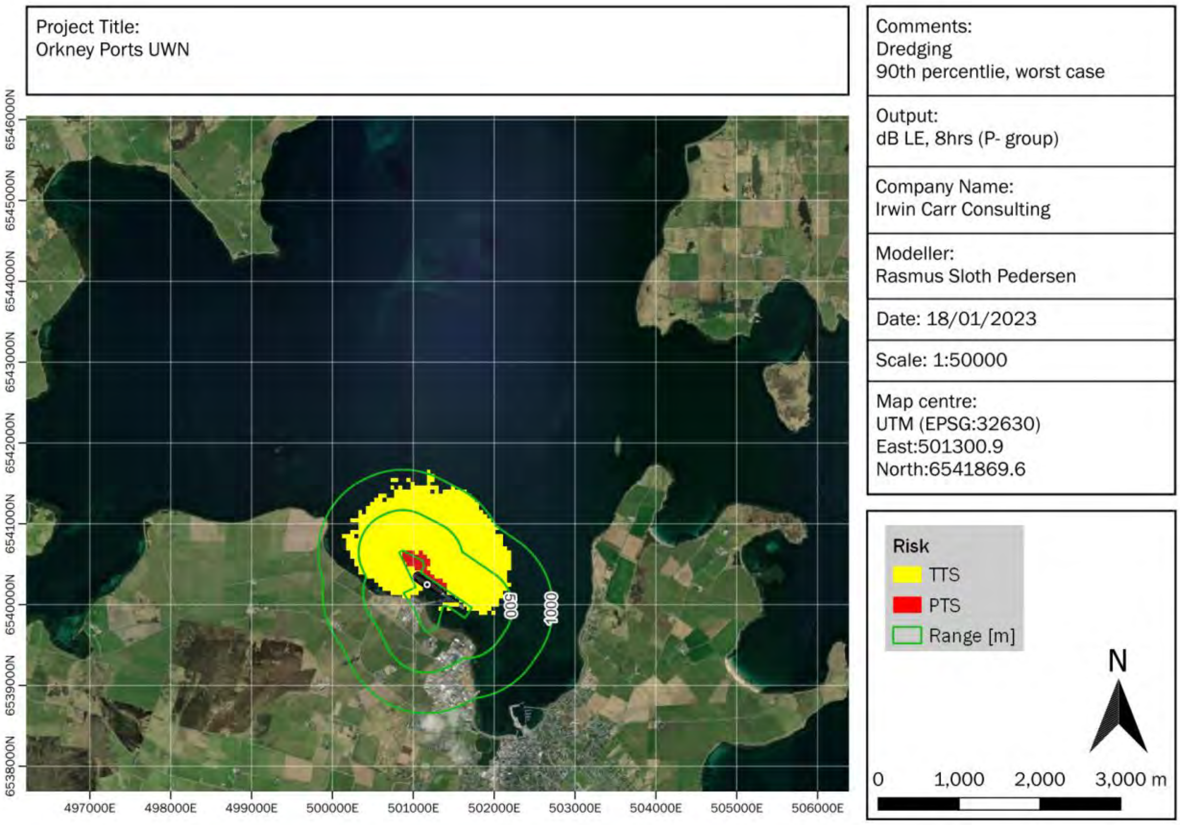


Figure 66. Dredging, L_E, 8hrs, P- group



Project Title:
Orkney Ports UWN

Comments:
Dredging
90th percentile, worst case

Output:
dB LE, 8hrs (P- group)

Company Name:
Irwin Carr Consulting

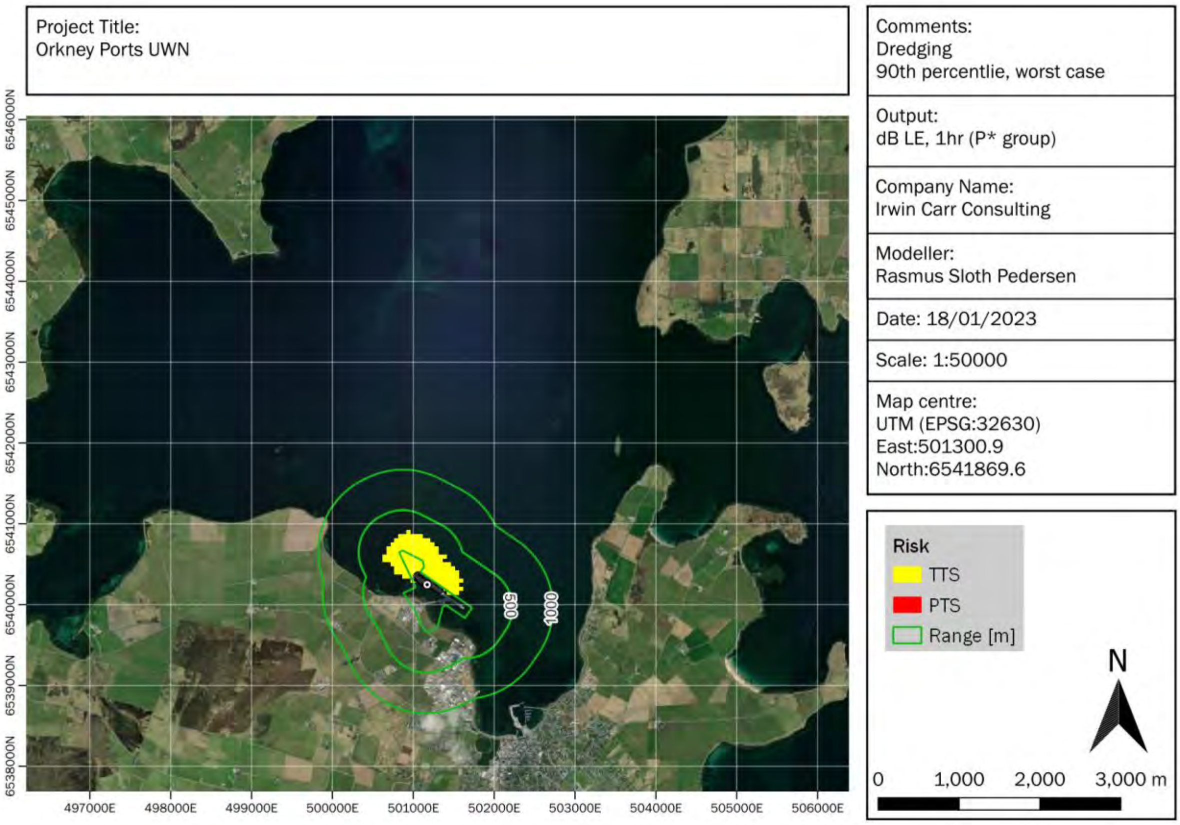
Modeller:
Rasmus Sloth Pedersen

Date: 18/01/2023

Scale: 1:50000

Map centre:
UTM (EPSG:32630)
East:501300.9
North:6541869.6

Figure 67. Dredging, L_E, 1hr, P* group



Project Title:
Orkney Ports UWN

Comments:
Dredging
90th percentile, worst case

Output:
dB LE, 1hr (P* group)

Company Name:
Irwin Carr Consulting

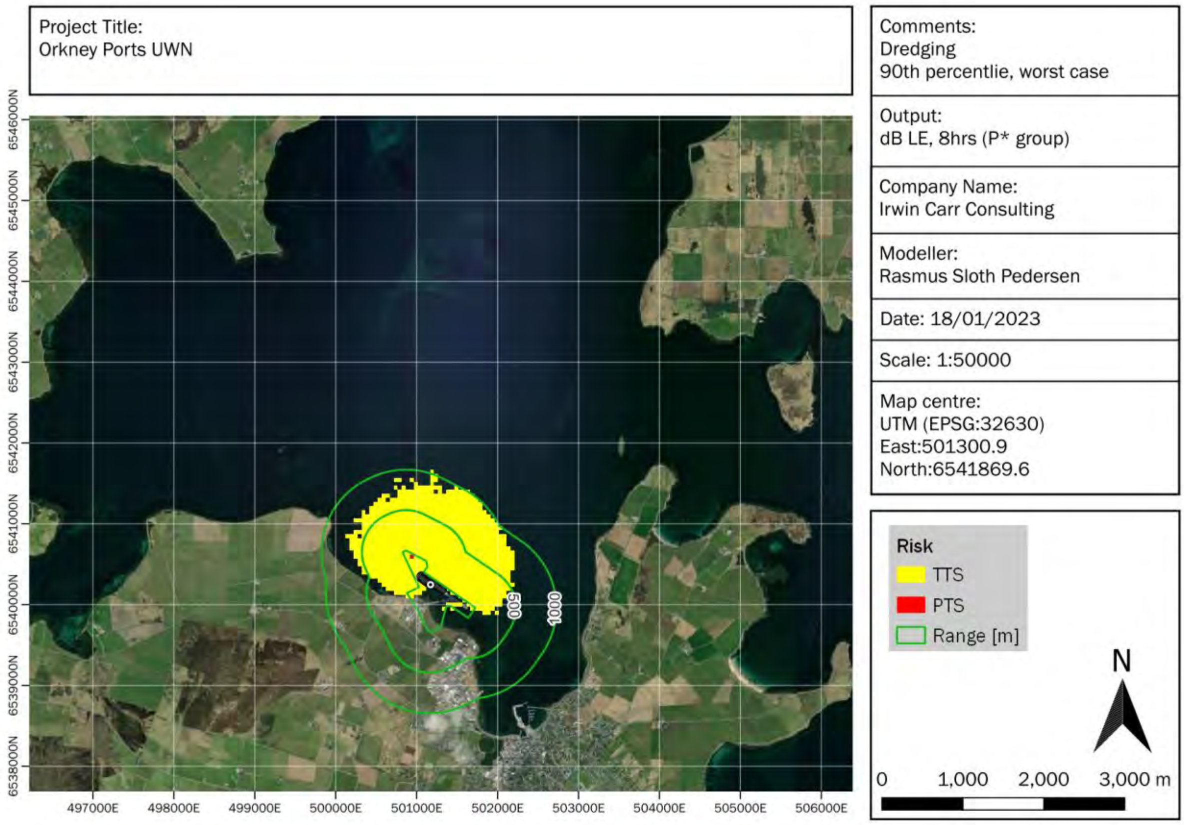
Modeller:
Rasmus Sloth Pedersen

Date: 18/01/2023

Scale: 1:50000

Map centre:
UTM (EPSG:32630)
East:501300.9
North:6541869.6

Figure 68. Dredging, L_E, 8hrs, P* group



Project Title:
Orkney Ports UWN

Comments:
Dredging
90th percentlie, worst case

Output:
dB LE, 8hrs (P* group)

Company Name:
Irwin Carr Consulting

Modeller:
Rasmus Sloth Pedersen

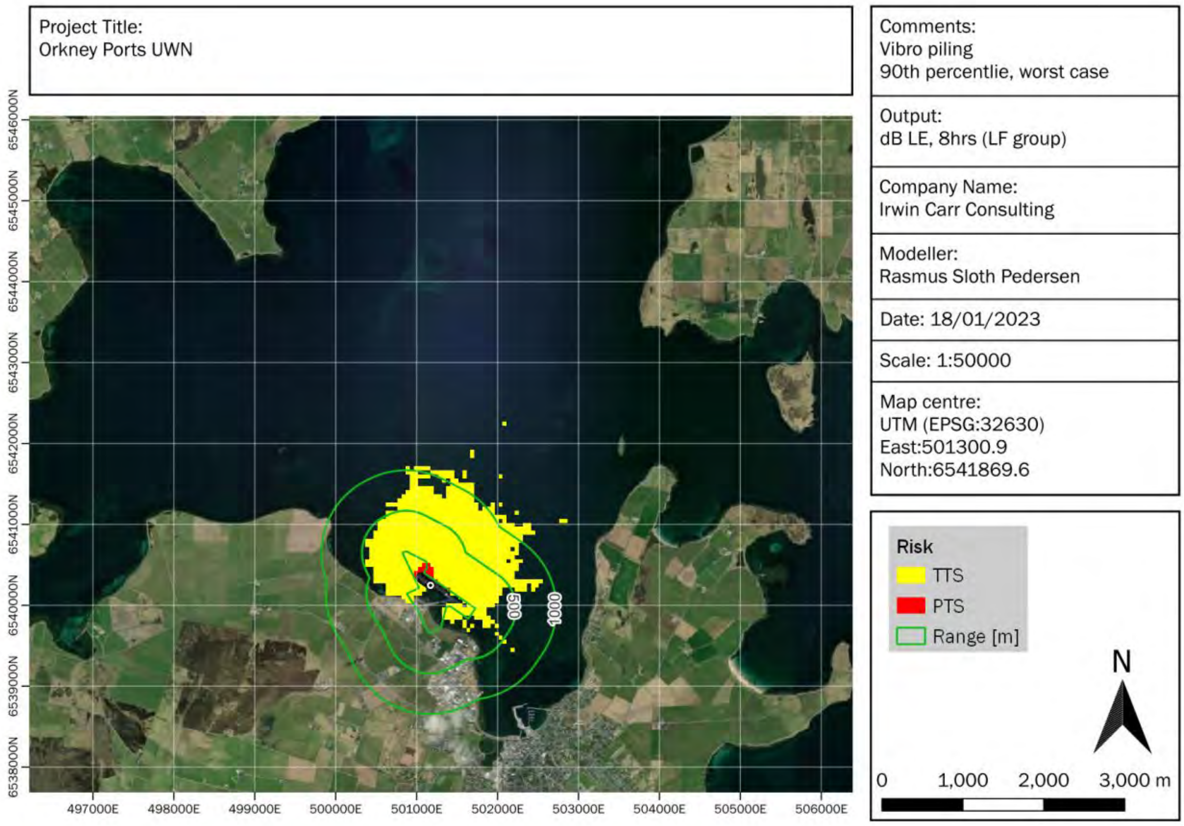
Date: 18/01/2023

Scale: 1:50000

Map centre:
UTM (EPSG:32630)
East:501300.9
North:6541869.6

Vibro Piling

Figure 69. Vibro piling, L_E, 8 hours, LF group



Project Title:
Orkney Ports UWN

Comments:
Vibro piling
90th percentile, worst case

Output:
dB LE, 8hrs (LF group)

Company Name:
Irwin Carr Consulting

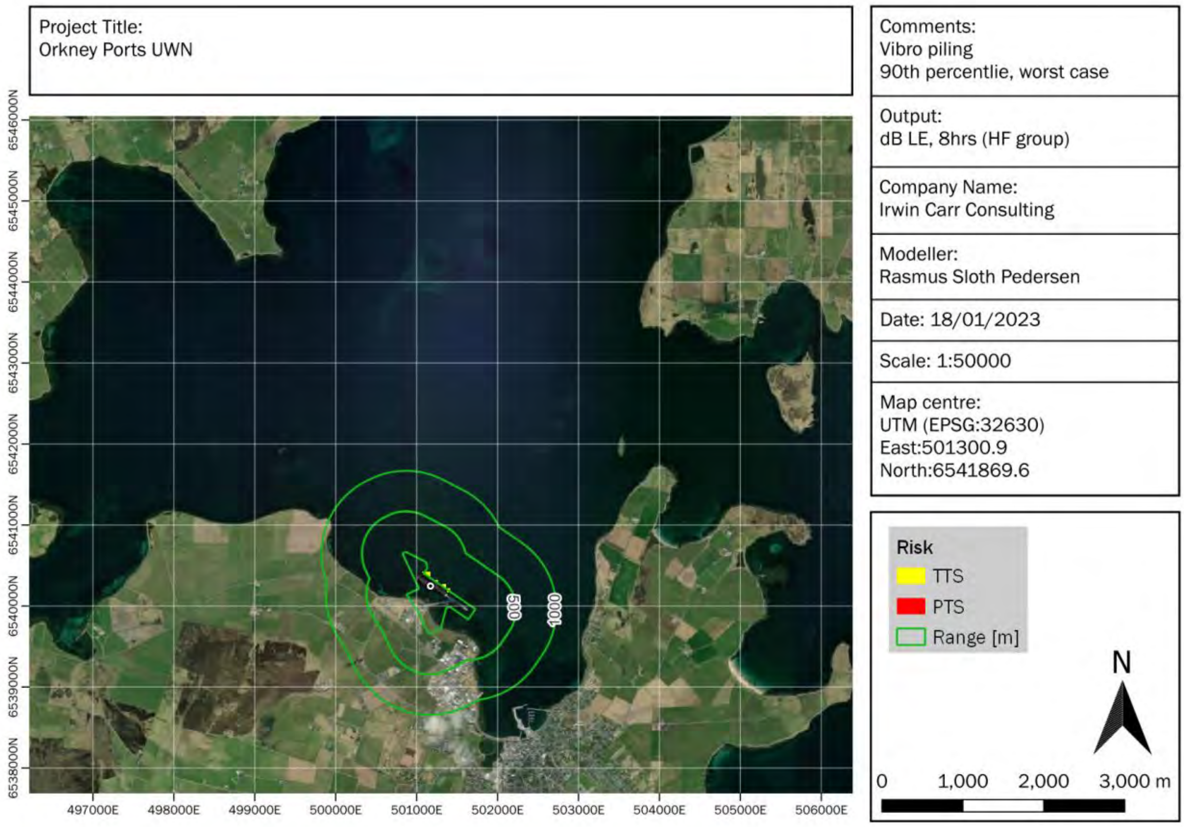
Modeller:
Rasmus Sloth Pedersen

Date: 18/01/2023

Scale: 1:50000

Map centre:
UTM (EPSG:32630)
East:501300.9
North:6541869.6

Figure 70. Vibro piling, L_E, 8 hours, HF group



Project Title:
Orkney Ports UWN

Comments:
Vibro piling
90th percentile, worst case

Output:
dB LE, 8hrs (HF group)

Company Name:
Irwin Carr Consulting

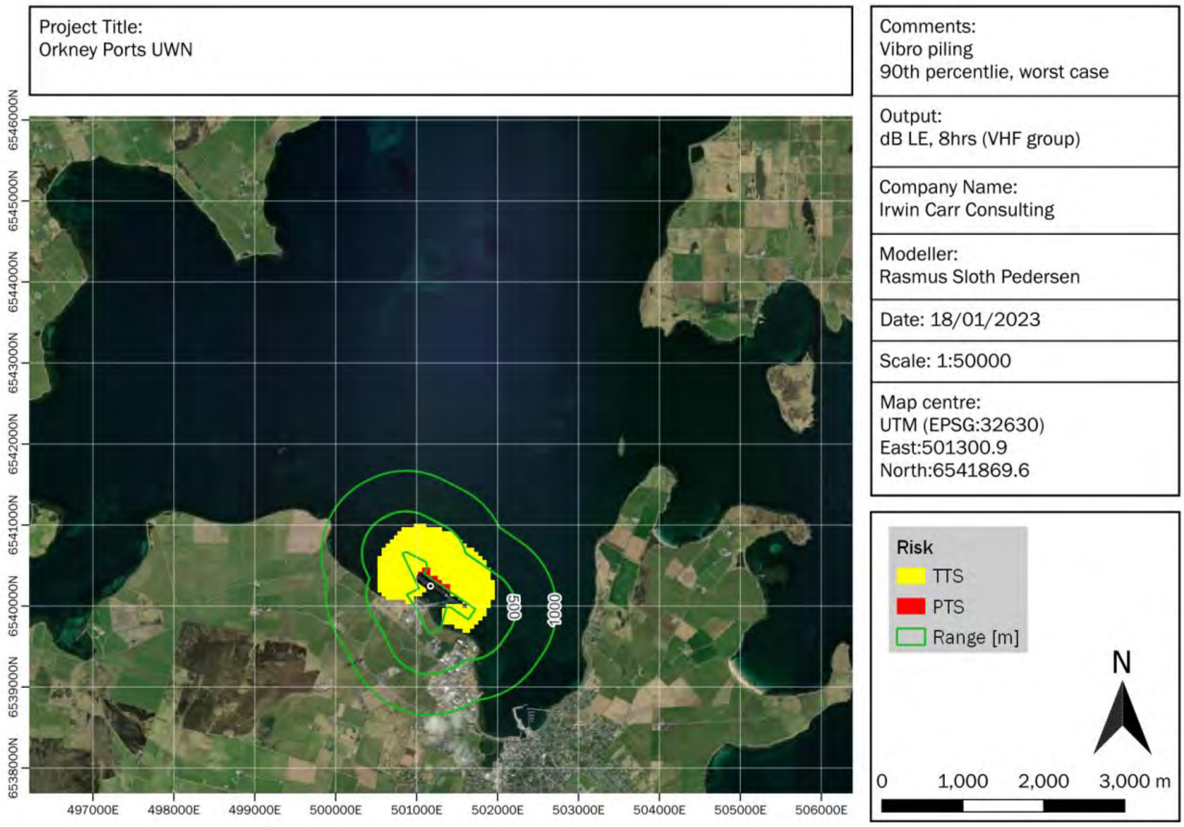
Modeller:
Rasmus Sloth Pedersen

Date: 18/01/2023

Scale: 1:50000

Map centre:
UTM (EPSG:32630)
East:501300.9
North:6541869.6

Figure 71. Vibro piling, L_E, 8 hours, VHF group



Project Title:
Orkney Ports UWN

Comments:
Vibro piling
90th percentile, worst case

Output:
dB LE, 8hrs (VHF group)

Company Name:
Irwin Carr Consulting

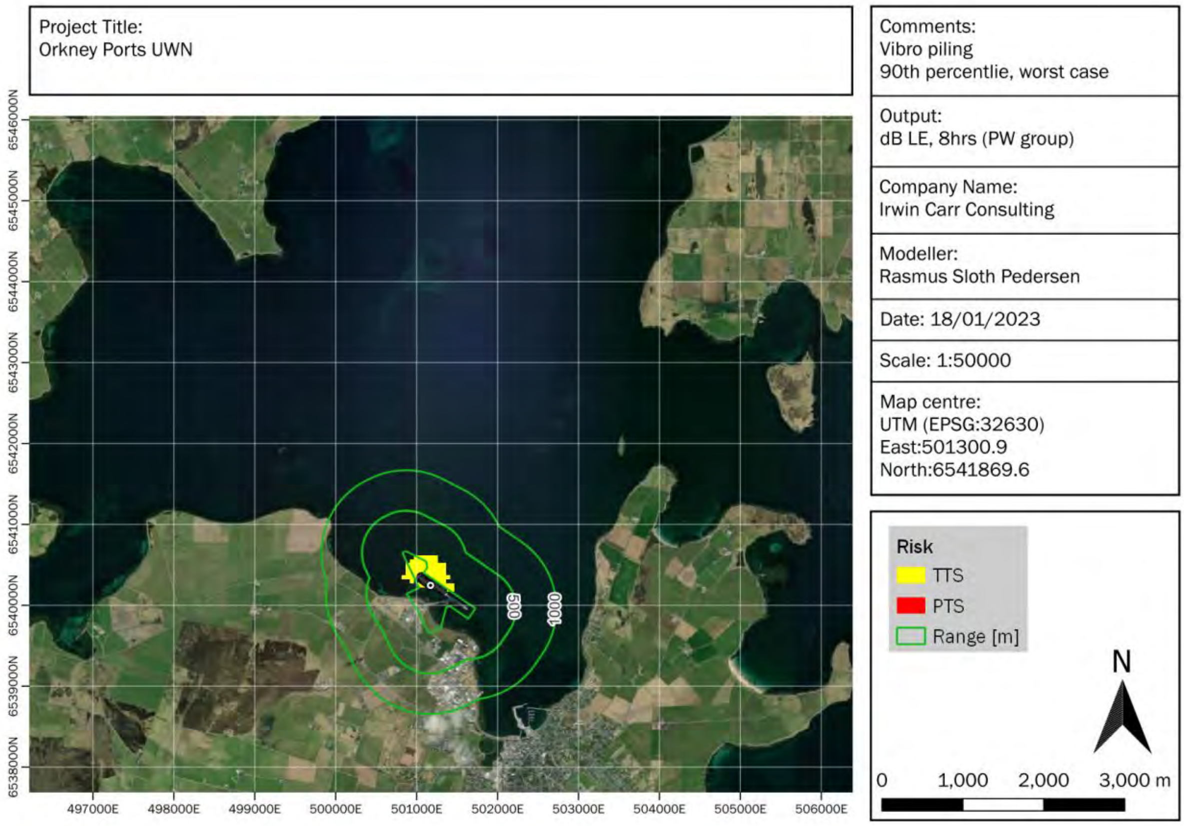
Modeller:
Rasmus Sloth Pedersen

Date: 18/01/2023

Scale: 1:50000

Map centre:
UTM (EPSG:32630)
East:501300.9
North:6541869.6

Figure 72. Vibro piling, L_E, 8 hours, PW group



Project Title:
Orkney Ports UWN

Comments:
Vibro piling
90th percentile, worst case

Output:
dB LE, 8hrs (PW group)

Company Name:
Irwin Carr Consulting

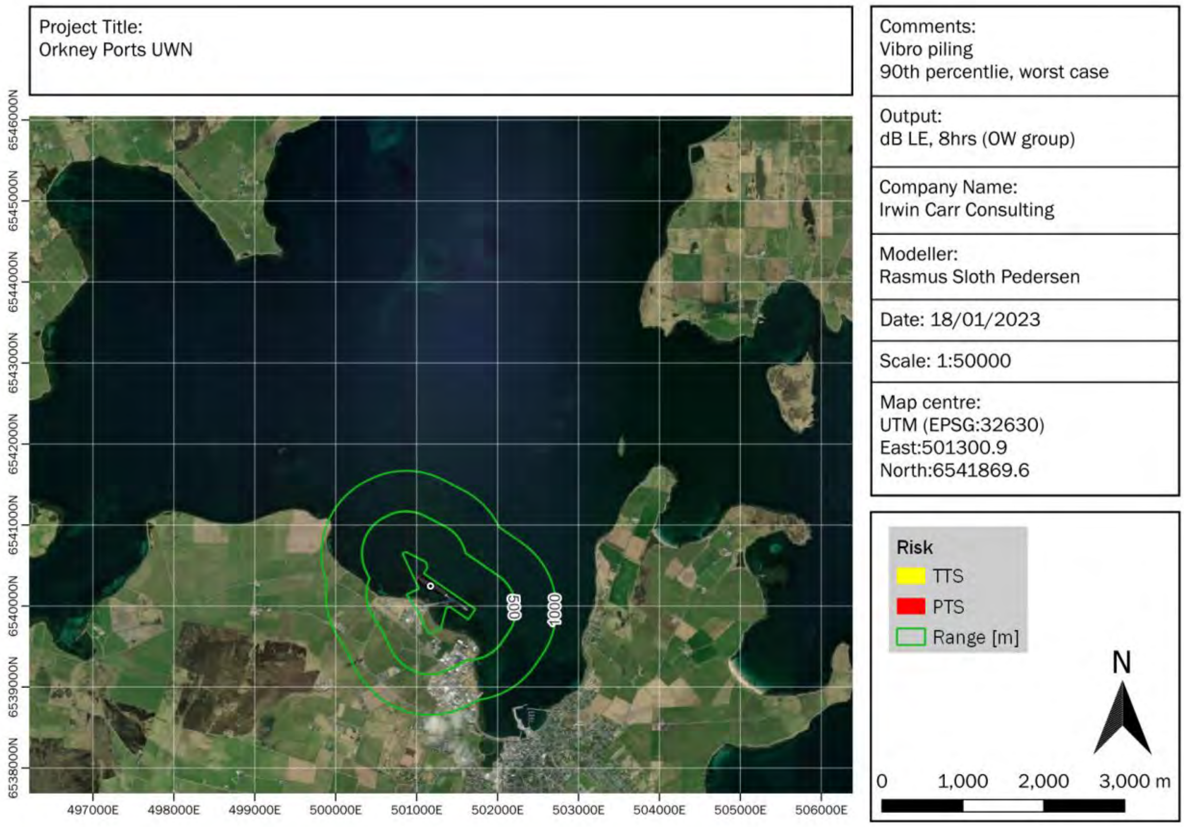
Modeller:
Rasmus Sloth Pedersen

Date: 18/01/2023

Scale: 1:50000

Map centre:
UTM (EPSG:32630)
East:501300.9
North:6541869.6

Figure 73. Vibro piling, LE, 8 hours, OW group



Project Title:
Orkney Ports UWN

Comments:
Vibro piling
90th percentile, worst case

Output:
dB LE, 8hrs (OW group)

Company Name:
Irwin Carr Consulting

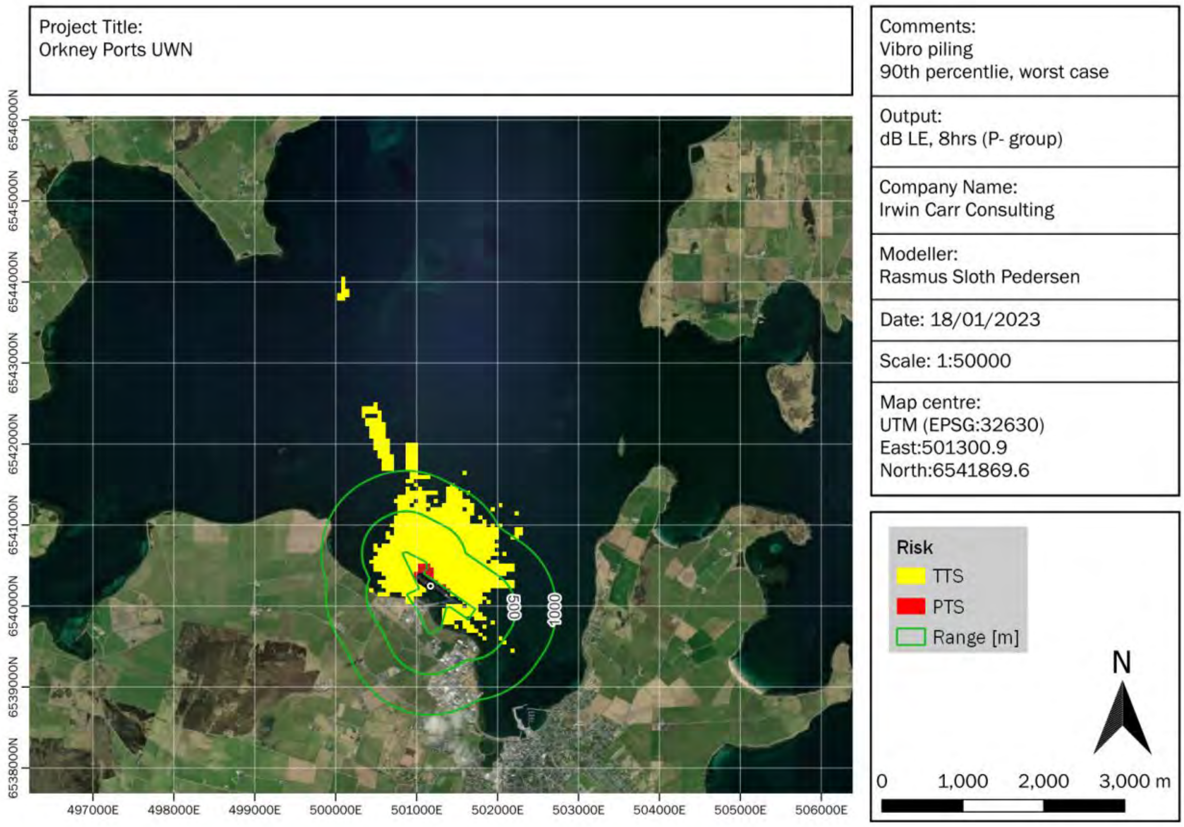
Modeller:
Rasmus Sloth Pedersen

Date: 18/01/2023

Scale: 1:50000

Map centre:
UTM (EPSG:32630)
East:501300.9
North:6541869.6

Figure 74. Vibro piling, LE, 8 hours, P- group (single "beam" projecting out is a model artefact and not representative of expected noise levels)



Project Title:
Orkney Ports UWN

Comments:
Vibro piling
90th percentile, worst case

Output:
dB LE, 8hrs (P- group)

Company Name:
Irwin Carr Consulting

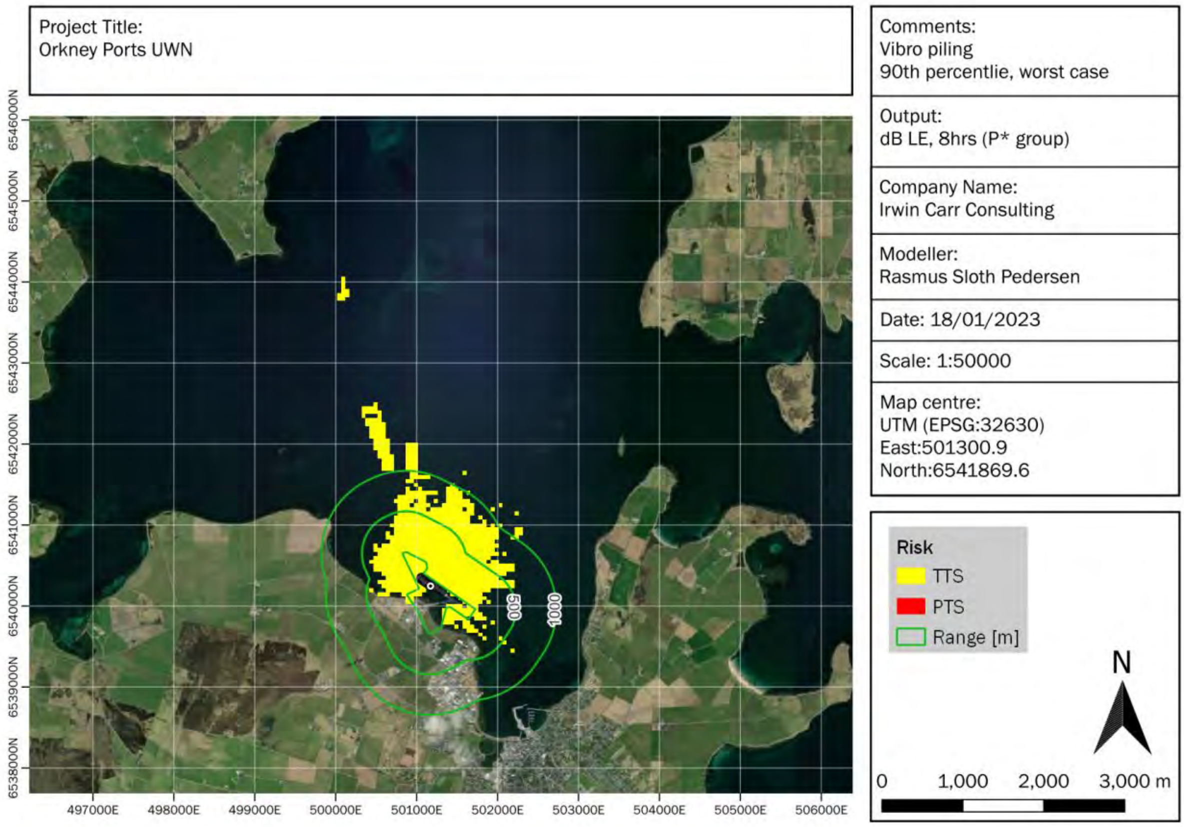
Modeller:
Rasmus Sloth Pedersen

Date: 18/01/2023

Scale: 1:50000

Map centre:
UTM (EPSG:32630)
East:501300.9
North:6541869.6

Figure 75. Vibro piling, L_E, 8 hours, P* group (single “beam” projecting out is a model artefact and not representative of expected noise levels)



Project Title:
Orkney Ports UWN

Comments:
Vibro piling
90th percentlie, worst case

Output:
dB LE, 8hrs (P* group)

Company Name:
Irwin Carr Consulting

Modeller:
Rasmus Sloth Pedersen

Date: 18/01/2023

Scale: 1:50000

Map centre:
UTM (EPSG:32630)
East:501300.9
North:6541869.6